




3 1761 11553868 8

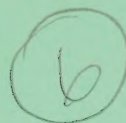


Digitized by the Internet Archive
in 2022 with funding from
University of Toronto

<https://archive.org/details/31761115538688>

CAI
EP
-1994
AGI v.6

Government
Publications



ARCHITECTURAL CONSERVATION TECHNOLOGY

VOLUME VI CONSERVATION OF MATERIALS

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICE
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA



Canadian Heritage
Parks Canada

Patrimoine canadien
Parcs Canada



Canada	Groupe
Communication	Communication
Group	Canada
Publishing	Édition

ARCHITECTURAL CONSERVATION TECHNOLOGY

VOLUME VI CONSERVATION OF MATERIALS

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICE
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA

© MINISTER OF SUPPLY AND SERVICES CANADA, 1994

Available in Canada through your local bookseller or by mail from Canada Communication Group - Publishing, Ottawa, Canada, K1A 0S9.

Published under the authority
of the Minister of the Department of Canadian Heritage,
Ottawa, 1994

CANADIAN CATALOGUING IN PUBLICATION DATA

Main entry under title:

ARCHITECTURAL CONSERVATION TECHNOLOGY

Issued also in French under title: Technologie de la conservation architecturale.

Complete work consists of 7 volumes.

Contents: Vol. I Project Management – Vol. II Heritage Recording – Vol. III Historic Site Analysis – Vol. IV Historic Site Design and Development – Vol. V Conservation Maintenance – Vol. VI Conservation of Materials – Vol. VII Period Construction Technology

ISBN 0-660-14657-6 (set); 0-660-14663-0 (Vol. VI);

DSS cat. no. W62-16/1993E (set);

W62-16/6-1993E – 7-1993E

1. Architecture – Canada – Conservation and restoration – Handbooks, manuals, etc.
2. Historic buildings – Canada – Conservation and restoration – Handbooks, manuals, etc.
3. Historic sites – Canada – Conservation and restoration – Handbooks, manuals, etc.
4. Cultural Property, Protection of – Canada.
 - I. Canada. Public Works Canada. Architectural and Engineering Services.
 - II. Heritage Conservation Program (Canada).

NA109.C32A72 1993

363.6'9'0971

C92-099751-1

NOTE: Since this manual was in production when federal government departments were restructured in 1993, it was impossible to update all in-text government references. The Canadian Parks Services (CPS) of Environment Canada is now Parks Canada of the Department of Canadian Heritage, and Public Works is now part of the Department of Government Services.

Included within the seven volumes of the ACT manual is both basic and specialized information on architecture, engineering and landscape works.

References at all levels within these disciplines, useful both in practice and in training, are intended to:

- introduce and familiarize the user with conservation concerns;
- serve as an "aide-mémoire" at both the design and managerial levels; and
- provide guidance to professional consultants responsible for recording and analysing historic structures, and applying recommended conservation methods to their protection and preservation.

All procedures outlined in these publications should be read in conjunction with the reference material, manufacturer's literature and the relevant Canadian Parks Service – National Historic Sites Management Directives.

In all matters where detailed specifications are required, such as building codes, fire regulations and the use of chemicals, the prevailing and local references and regulations must be consulted and applied.

Please note that the ACT manual has been prepared within the context of Parks Canada Policy (1979). The newly proposed Canadian Parks Service Policy (1990) establishes additional and broader directions that, however, do not alter the orientation of the technical material covered. The ACT manual reflects the well established principles of conservation as defined by national and international charters and conventions – see Vol. I Appendix.

Within the proposed policy, the Cultural Resource Management (CRM) section (see Vol. I, Appendix 5.17) establishes the overall framework for the conservation and presentation of the cultural assets administered by CPS, on all CPS properties, including those in National Historic Sites, Historic Canals, National Parks, National Marine Parks, and other CPS properties. In the event of a conflict between the direction provided by the ACT manual and that provided by CRM Policy, the latter applies.

Although great care has been taken to trace the ownership of copyrighted material used in the text (including illustrations), the demise or apparent disappearance of some publishing firms has made tracing nearly impossible. Therefore, the authors and publisher welcome any information enabling them to rectify references and credits in subsequent editions.

STANDING ORDERS

- ☐ Standing Orders are accepted for periods of up to three years. At the end of the period requested (see below), a notice will be sent asking you to confirm that you wish continued provision of this service.
- ☐ Invoices will be sent on quarterly basis.
- ☐ The Canada Communication Group - Publishing must be informed in writing of a change of address and/or a change in quantities.
- ☐ Any outstanding balances not paid within 30 days of the date of the invoice could jeopardize the continued provision of this service.

The Standing Order form below should be completed and returned to:

Canada Communication Group - Publishing

Ottawa, Canada K1A 0S9

STANDING ORDER FORM

Catalogue number	Title	Number of Copies	Period Requested
W62-16/1E	Project Management (Vol. 1)		<input type="checkbox"/> 1 year <input type="checkbox"/> 2 years <input type="checkbox"/> 3 years
W62-16/2E	Heritage Recording (Vol. 2)		<input type="checkbox"/> 1 year <input type="checkbox"/> 2 years <input type="checkbox"/> 3 years
W62-16/3E	Historic Site Analysis (Vol. 3)		<input type="checkbox"/> 1 year <input type="checkbox"/> 2 years <input type="checkbox"/> 3 years
W62-16/4E	Historic Site Design and Development (Vol. 4)		<input type="checkbox"/> 1 year <input type="checkbox"/> 2 years <input type="checkbox"/> 3 years
W62-16/5E	Conservation Maintenance (Vol. 5)		<input type="checkbox"/> 1 year <input type="checkbox"/> 2 years <input type="checkbox"/> 3 years
W62-16/6E	Conservation of Materials (Vol. 6)		<input type="checkbox"/> 1 year <input type="checkbox"/> 2 years <input type="checkbox"/> 3 years
W62-16/7E	Period Construction Technology (Vol. 7)		<input type="checkbox"/> 1 year <input type="checkbox"/> 2 years <input type="checkbox"/> 3 years

A service fee of \$3.00 per volume is charged per address to which standing orders are shipped (irrespective of the number of copies shipped to an address, and irrespective of the period requested, i.e. from 1 to 3 years). If applicable, add 7% GST.

Purchase orders are accepted from governments, registered companies and educational institutions. (Federal Government - Please use purchase orders only)

◆ Purchase Order No.: | | | | | | | | | |

Others are required to prepay the \$3.00 service fee.
(Orders from outside Canada - payable in US dollars).

☐ Cheque/Money Order (payable to the Receiver General for Canada) enclosed.

[illegible]

Credit Card Expiry Date: /

Date: / /

Signature: _____

SHIP TO:

NAME _____

FIRM/ORGANIZATION

ADDRESS	CITY
---------	------

PROVINCE _____ POSTAL CODE | | | | |

The following information is being furnished to you for your information and use only. It is not to be used for any other purpose. The information is being furnished to you for your information and use only. It is not to be used for any other purpose. The information is being furnished to you for your information and use only. It is not to be used for any other purpose.

Name	Address	City
John Doe	123 Main St	New York
Jane Smith	456 Elm St	Los Angeles
Bob Johnson	789 Oak St	Chicago
Alice Brown	101 Pine St	San Francisco
Charlie White	202 Cedar St	Houston
Diana Green	303 Birch St	Phoenix
Frank Black	404 Spruce St	Dallas
Grace King	505 Willow St	San Antonio
Henry Lee	606 Ash St	Fort Worth
Ivy Hill	707 Hickory St	Austin
Jack Adams	808 Maple St	Jacksonville
Karen Baker	909 Poplar St	Nashville
Leo Clark	1010 Sycamore St	Portland
Mia Evans	1111 Walnut St	Seattle

CONTENTS

Architectural Conservation Technology (ISBN 0-660-14657-6; DSS Cat. no. W62-16/1993E) is a manual of seven volumes. Each volume may be bought separately. Here are the contents and numbers for each one.

VOLUME I: PROJECT MANAGEMENT

ISBN: 0-660-14658-4
DSS: W62-16/1-1993E

- 1 STANDARDS FOR ARCHITECTURAL CONSERVATION
- 2 PROJECT PROCEDURES
- 3 INFORMATION MANAGEMENT
- 4 PROTECTION OF HISTORIC FABRIC
- 5 PERSONNEL HEALTH AND SAFETY
- 6 USE OF CONSULTING SERVICES FOR CONSERVATION PROJECTS

VOLUME II: HERITAGE RECORDING

ISBN: 0-660-14659/2
DSS: W62-16/2-1993E

- 1 INTRODUCTION
- 2 HERITAGE RECORDING TECHNIQUES
- 3 TYPES OF HERITAGE RECORDS
- 4 INCORPORATING PHOTOGRAPHS INTO TECHNICAL DRAWINGS

VOLUME III: HISTORIC SITE ANALYSIS

ISBN: 0-660-14660-6
DSS: W62-16/3-1993E

- 1 CATEGORIES AND LEVELS OF ANALYSIS
- 2 DETERMINATION OF SCOPE
- 3 INVESTIGATION OF COMPARATIVE SOURCES
- 4 ARCHITECTURAL ANALYSIS: GENERAL ASSESSMENT
- 5.1 STRUCTURAL ENGINEERING ANALYSIS: GENERAL ASSESSMENT
- 5.2 STRUCTURAL ENGINEERING ANALYSIS: STRUCTURAL DIAGNOSIS

- 5.3 STRUCTURAL ENGINEERING ANALYSIS: STRUCTURAL DEFORMATION
- 6.1 INVESTIGATION AND ANALYSIS OF SITE SERVICES: PERIOD PLUMBING AND DRAINAGE
- 6.2 INVESTIGATION AND ANALYSIS OF SITE SERVICES: PERIOD HEATING AND VENTILATION
- 6.3 INVESTIGATION AND ANALYSIS OF SITE SERVICES: PERIOD LIGHTING
- 7.1 INVESTIGATION AND ANALYSIS OF MARINE AND INDUSTRIAL SITES: PERIOD MACHINERY
- 7.2 INVESTIGATION AND ANALYSIS OF MARINE AND INDUSTRIAL SITES: PERIOD VESSELS
- 7.3 INVESTIGATION AND ANALYSIS OF MARINE AND INDUSTRIAL SITES: INDUSTRIAL SITES
- 8 INVESTIGATION AND ANALYSIS OF LANDSCAPES
- 9 ENVIRONMENTAL INVESTIGATION AND ANALYSIS
- 10.1 SPECIAL INVESTIGATION AND ANALYSIS: MATERIAL SAMPLES
- 10.2 SPECIAL INVESTIGATION AND ANALYSIS: COLOUR
- 10.3 SPECIAL INVESTIGATION AND ANALYSIS: MOISTURE CONTENT

VOLUME IV: HISTORIC SITE DESIGN AND DEVELOPMENT

ISBN: 0-660-14661-4
DSS: W62-16/4-1993E

- 1 LEVELS OF INTERVENTION
- 2 DESIGN CRITERIA
- 3.1 INTERIM PROTECTION: DESIGN STANDARDS
- 3.2 INTERIM PROTECTION: STABILIZATION OF HISTORIC STRUCTURES
- 3.3 INTERIM PROTECTION: ENVIRONMENTAL CONTROLS
- 3.4 INTERIM PROTECTION: HISTORIC GARDENS AND LANDSCAPES

CONTENTS

- 4.1 STABILIZATION OF MASONRY STRUCTURES: CLEANING
 - 4.1.1 STABILIZATION OF MASONRY STRUCTURES: REINFORCEMENT
 - 4.1.2 STABILIZATION OF MASONRY STRUCTURES: EPOXY REPAIR
 - 4.1.3 STABILIZATION OF MASONRY STRUCTURES: REPOINTING
- 4.2 STABILIZATION OF WOOD STRUCTURES: SPLICING AND REPAIR
 - 4.2.1 STABILIZATION OF WOOD STRUCTURES: CHEMICAL CONSOLIDATION
 - 4.2.2 STABILIZATION OF WOOD STRUCTURES: CHINKING
- 4.3 STABILIZATION OF IRON AND STEEL STRUCTURES
- 4.4 STABILIZATION OF WINDOWS AND DOORS
- 4.5 STABILIZATION OF ROOFING MATERIALS
- 4.6 STABILIZATION OF HARDWARE
- 4.7 STABILIZATION OF PERIOD MACHINERY
- 4.8 STABILIZATION OF PERIOD VESSELS
- 4.9 STABILIZATION OF ARCHAEOLOGICAL SITES
- 5.1 REHABILITATION: DESIGN STANDARDS
- 5.2 REHABILITATION: OCCUPANCY AND LAYOUT
- 5.3 REHABILITATION: STRUCTURAL MODIFICATIONS
- 5.4 REHABILITATION: FIRE PROTECTION
- 5.5 REHABILITATION: MUSEUM ENVIRONMENTS
- 5.6 REHABILITATION: HISTORIC GARDENS AND LANDSCAPES
- 6.1 RESTORATION: PERIOD MACHINERY
- 6.2 RESTORATION: PERIOD VESSELS
- 6.3 RESTORATION: HISTORIC GARDENS AND LANDSCAPES
- 7.1 SPECIAL TECHNIQUES: DISMANTLING AND REASSEMBLY OF WOODEN STRUCTURES
- 7.2 SPECIAL TECHNIQUES: MOVING HISTORIC STRUCTURES

VOLUME V: CONSERVATION MAINTENANCE

ISBN: 0-660-14662-2
DSS: W62-16/5-1993E

- 1 PREPARATION OF MAINTENANCE MANUALS
- 2.1 MAINTENANCE PROCEDURES: HOUSEKEEPING PROGRAMS
- 2.2 MAINTENANCE PROCEDURES: MAINTENANCE INSPECTIONS
- 2.3 MAINTENANCE PROCEDURES: PERIODIC WORKS
- 3 EMERGENCY WORKS
- 4 MONITORING PROGRAMS

VOLUME VI: CONSERVATION OF MATERIALS

ISBN: 0-660-14663-0
DSS: W62-16/6-1993E

- 1.1 CONCRETE: COMPOSITION AND PROPERTIES
- 1.2 CONCRETE: DETERIORATION AND DEFECTS
- 1.3 CONCRETE: CONSOLIDATION AND REPAIR
- 2.1 MASONRY: STRUCTURE AND PROPERTIES
- 2.2 MASONRY: DETERIORATION
- 3.1 MORTAR: COMPOSITION AND PROPERTIES
- 3.2 MORTAR: DETERIORATION
- 4.1 METALS: DETERIORATION OF CAST AND WROUGHT IRON
- 4.2 METALS: CONSOLIDATION AND REPAIR
- 5.1 WOOD: STRUCTURE AND PROPERTIES
- 5.2 WOOD: GROWTH, CONVERSION AND SEASONING DEFECTS
- 5.3 WOOD: WEATHERING AND AGING
- 5.4 WOOD: FUNGAL DECAY AND STAINING
- 5.5 WOOD: DAMAGE BY INSECTS AND MARINE BORERS
- 5.6 WOOD: DAMAGE BY HEAT AND FIRE
- 5.7 WOOD: FIRE PROTECTION TREATMENTS
- 6.1 WOODWORK: FINISHING AND WORKING CHARACTERISTICS

CONTENTS

- 6.2 WOODWORK: DETERIORATION AND DEFECTS
- 6.3 WOODWORK: CONSOLIDATION AND REPAIR
- 7.1 PAINT: COMPOSITION AND PROPERTIES: OIL-BASED PAINTS
- 7.2 PAINT: DETERIORATION
- 7.3 PAINT: ANALYSIS
- 7.4 PAINT: INTERVENTION
- 8.1 WALLPAPER: COMPOSITION AND PROPERTIES
- 8.2 WALLPAPER: DETERIORATION
- 8.3 WALLPAPER: ANALYSIS AND REMOVAL
- 8.4 WALLPAPER: CONSOLIDATION AND REPAIR
- 12.1 PERIOD PAINTING: OIL, WHITEWASH, DISTEMPER AND OTHER MEDIA
- 12.2 PERIOD PAINTING: WAXING, OILING, STAINING AND VARNISHING
- 12.3 PERIOD PAINTING: DECORATIVE PAINTING
- 13.1 PERIOD SERVICING: PLUMBING AND DRAINAGE
- 13.2 PERIOD SERVICING: HEATING AND VENTILATION
- 13.3 PERIOD SERVICING: PERIOD LIGHTING
- 13.4 PERIOD SERVICING: FIRE PROTECTION AND SECURITY
- 14 PERIOD LANDSCAPING

VOLUME VII: PERIOD CONSTRUCTION TECHNOLOGY

ISBN: 0-660-14664-9
DSS: W62-16/7-1993E

- 1 CONSTRUCTION ORGANIZATIONAL DEVELOPMENT IN CANADA
- 2 PERIOD SITE WORK
- 3 PERIOD CONCRETE WORK
- 4.1 PERIOD MASONRY: ROUGH STONE WORK
- 4.2 PERIOD MASONRY: CUT STONE WORK
- 5.1 PERIOD BRICKLAYING AND TILING: BRICKWORK
- 5.2 PERIOD BRICKLAYING AND TILING: TERRA COTTA AND TILE WORK
- 6 PERIOD METAL WORK
- 7.1 PERIOD CARPENTRY: LOG CONSTRUCTION
- 8.1 PERIOD JOINERY: DOOR MAKING
- 8.2 PERIOD JOINERY: WINDOW MAKING
- 8.3 PERIOD JOINERY: PANELLING, FITTINGS AND DECORATIVE WORK
- 8.4 PERIOD JOINERY: STAIR BUILDING
- 9.1 PERIOD ROOFING: SHINGLE ROOFING
- 9.2 PERIOD ROOFING: SLATE ROOFING
- 10 PERIOD GLAZING AND GLASS
- 11 PERIOD PLASTERING

VOLUME VI

CONSERVATION OF MATERIALS

1.1

CONCRETE

COMPOSITION AND PROPERTIES

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: A. POWTER

CONTENTS

1.0 INTRODUCTION

2.0 DEFINITIONS

3.0 MATERIALS

3.1 CEMENT

3.2 AGGREGATE

3.3 WATER

3.4 ADMIXTURES

4.0 BIBLIOGRAPHY

1.0 INTRODUCTION

When building with wood and stone, the builder works with the materials as they occur naturally. The properties and characteristics of human-made materials such as cement and concrete are determined as much by the manufacturing process and the materials used, as by the design and the practices used on the construction site.

Knowledge and understanding of cement materials has slowly improved from Roman times until the present. It was not until the 1930s that the fundamentals of cement and concrete technology were well understood. Even today, almost 150 years after the first patent for Portland cement, many gaps in the knowledge remain.

Concrete manufacture and use and thus its properties, were influenced by the knowledge and perceptions at the time of construction. It is important that architects and engineers involved in preservation of historic concrete structures be familiar with the material of the period.

This article is a brief introductory description, with bibliography, of the composition, properties and manufacture of historic concrete, particularly regarding its durability and potential for deterioration. Historic concrete construction practices are described in a separate publication, "Period Concrete Work." The bibliography is the most important part of this article for conservators involved in analysis or preservation of a historic concrete structure. Many books and millions of words have been written on concrete technology in the past 150 years. Consequently this bibliography is highly selective and is annotated. Excluded works are not necessarily better or worse; they simply have not been reviewed by the author or recommended by other conservators.

2.0 DEFINITIONS

Portland Cement: the product of burning at approximately 1300°C, it is an artificially prepared and precisely controlled mixture of limestone and clay (silicates and aluminates). The resulting clinker is ground to produce a hydraulic cement.

Natural Cement: the product of burning limestone which, in its natural state, contains sufficient silicious impurities (3

percent to 4 percent) to produce a lime with hydraulic properties. Most of the cements manufactured in Canada between the late 1830s and the late 1880s were of this type.

Hydration: a complex process which involves several simultaneous series of chemical reactions during which the main constituents of cement, the calcium silicates and aluminates, react with water to produce hydrates and numerous other compounds. The fact that the reaction products are insoluble gives concrete its characteristic durability in the presence of water.

Setting and Hardening: setting occurs when concrete, mixed with water, loses its plasticity and becomes friable. It will not become plastic again upon mixing with water. During hardening, the friable mass becomes progressively more tightly bonded together.

3.0 MATERIALS

3.1 CEMENT

Cement is produced when an intimate mixture of calcareous (lime) and argillaceous (clay) materials are burned and then ground to a fine powder. When mixed with water, the powder becomes adhesive, capable of bonding fragments of stone (aggregate) into a mass. The basic process has remained the same since Roman times, although individual parts of the manufacturing process have changed (burning temperatures are higher, grinding is finer, lime-clay proportions precisely calibrated) and the chemistry of the process has become progressively better understood.

Throughout the late 18th and 19th centuries, research and developments in cement led in two different directions – full exploitation of natural hydraulic cement and development of artificial hydraulic cement. The artificial cements were stronger and more widely used by the 1880s, but it should not be forgotten that natural cements continued to form an important part of the industry throughout the century.

The research of Smeaton and Parker in the late 18th century led to the location, identification and use of high quality natural hydraulic limes. Their work tested and identified sources of raw materials suitable for engineering purposes.

A few years later Vicat and Frost took the first steps toward the production of an artificial hydraulic cement. Vicat's experiments, on which Frost may have based his 1811 patent, yielded several advances:

- a. hydraulic material could be made from a non-hydraulic lime and clay mixture;
- b. the proportions of the raw materials were significant to the quality of the end product; and
- c. the quantity of mixing water influenced the strength of the resulting concrete.

Vicat also concluded (theoretically) that the silica of the day was essential to the hardening process.

Although Joseph Aspdon's 1824 patent for Portland cements is acknowledged as the milestone of its invention, the key to the high quality material we know today was high temperature burning. This was not included in a patent until 1852 and within ten years, the reputation of Portland cement as a reliable engineering material was well established as it took an ever increasing share of the market.

Further refinements of the burning and grinding processes and research into hydration and the roles of silica and alumina led to a material that, by the 1920s, was virtually the same as the material we know today.

This series of developments and their timing, indicates that historic concrete structures in Canada built prior to the 1880s may still contain non-Portland cements and that the cement used in structures built prior to the 1920s could vary considerably from the modern material.

3.2 AGGREGATE

The aggregate, which can make up as much as 80 percent of the volume of the concrete, is not simply an inert filler. Researchers have for many years been aware that the characteristics of the aggregate often control the quality and many properties of the concrete. Ideally, aggregate should have a compressive strength equal to that of the cement-paste, be chemically inert in water and be clean to ensure a good cement-aggregate bond. Grading of aggregate is also important. Ideally it should be continually graded so that the smaller size grains fill the interstices between the larger sizes, keeping the amount of cement-to-paste to a minimum. The grade and shape of the aggregate will also affect the workability of the concrete. An extremely rough, angular

aggregate is less workable and may require that more water be added to the mix to increase its workability. Sharp aggregate can also hinder compaction.

Cement researchers have for some time shown a preference for sharp aggregate over rounded materials in order to achieve a strong cement-aggregate bond, despite the fact that sharp aggregate is less workable. There is evidence that workers added water during mixing to overcome this. Researchers at the turn of the century (1906) were aware of the problems of using porous aggregates in a dry mix. The aggregate absorbed water and reduced workability. They investigated the effect of porous material on cement-aggregate bond strength. Very few researchers prior to 1900 were concerned about aggregate material itself; indeed the phenomenon of reactive aggregates was not investigated until much later. The importance of clean aggregate for greater tensile strength was established late in the 19th century.

3.3 WATER

The addition of water to the cement-aggregate mix begins a complex sequence of chemical reactions – hydration, setting and hardening. The ratio of water to cement is one of the most important factors governing the strength and durability of concrete. There must be sufficient water to coat and hydrate every particle of cement but not so much that when the concrete dries, large voids previously occupied by water, will be left. Although Vicat identified these phenomena in the 1830s, it was customary in the early 1900s to use excess water to simplify mixing and placement.

Today, mixing water is kept free from impurities and salts. However, early research indicated that these impurities were not harmful. Sea water was often used when available and even salt, sugar or glycerine was added to mixing water to prevent freezing during cold-weather pouring. Some builders adopted the practice of adding fine clay to mixing water to improve the waterproofing characteristics of the finished concrete.

3.4 ADMIXTURES

A variety of materials were added to concrete during mixing to alter its properties. Most of these additives can reduce durability. Salt and clay have been mentioned above. Other materials include sugar, chopped straw, earth and sticks. Air-entraining and other admixtures used today do not occur in historic concrete.

4.0 BIBLIOGRAPHY

American Concrete Institute. n.d. *Durability of Concrete*. Detroit.

_____. n.d. *Concrete Primer*. Detroit.

_____. n.d. *Durability of Concrete Construction*. Detroit.

Baker, I.O. 1890. *A Treatise on Masonry Construction*. John Wiley & Sons, New York.

A representative text of the 1890s with a good section on several aspects of concrete work, particularly foundations, mixing and proportioning.

Burnell, G.R. 1856. *Treatise on Limes and Cements*. Weale, London.

Canadian Portland Cement Association. *Design and Control of Concrete Mixtures*. Ottawa.

Covers all the basics required for an understanding of the properties and characteristics of the material as it is understood today. Published in 14 editions over the last 60 years, this is an essential text.

Collins, P. 1959. *Concrete: Vision of a New Architecture*. Faber and Faber, London.

Contains several excellent chapters on the use of concrete and a predecessor, rammed earth construction, in Britain and France. Describes the various construction technologies from which concrete developed.

Concrete Society. 1971. *The Weathering of Concrete*. Proceedings of a symposium held at the RIBA, London.

Dobsen, E. 1850. *Foundations and Concrete Work*. Weale, London.

Contains many good descriptions of mass concrete and pre-cast works for marine and heavy civil work. Useful sections on cyclopean concrete and mixing.

Earle, G., and T. Earle. 1925. *The Making and Testing of Portland Cement*. Hull.

Faija, H. 1884. *Portland Cement for Users*. Crosby Lockwood.

Another reference oriented to the builder using concrete from a significant year in its use.

Godwin, G. 1837. *The Nature and Properties of Concrete and its Application to Construction up to the Present Period*. Proceedings of the RIBA, Vol. 1.

Hutcheson, H.B. *Concrete*. Canadian Building Digest No. 15. National Research Council, Ottawa.

Kidder, F.E. 1905. *Building Construction and Superintendence: Part I, Mason's Work*. Comstock, New York.

Lea, Sir F. 1970. *The Chemistry of Cement and Concrete*. Edward Arnold, Glasgow, UK.

Essential reading, probably the standard text on the subject. One chapter on each aspect of the subject such as manufacture, hydration, aggregates, etc., is sufficiently basic and readable to make this an essential text.

Nelson, H. ed. 1976. *A Selection of Historic American Papers on Concrete-1876 to 1976*. ACI, Detroit.

A collection of US based papers that mark various milestones in concrete development. Provides the original text of several papers mentioned in other secondary sources. Ward's (1882) and Ransome's papers are particularly useful. Biography of each writer is included.

Pasley, Sir C. 1847. *Limes and Calcareous Cements*. Weale, London.

Pasley was primarily a researcher early in the 19th century working with the British Military engineers. His books provide a useful insight into official and academic knowledge of the subject. Pasley's research went off on tangents periodically, with misleading results for the science of cements and limes but he is a significant researcher.

Sereda, P.J. 1970. *The Structure of Porous Building Materials*. Canadian Building Digest No. 127. National Research Council, Ottawa.

Sereda, P.J., and R. F. Feldman. 1970. *Wetting and Drying of Porous Building Materials*. Canadian Building Digest No. 130. National Research Council, Ottawa.

Smeaton J.A. 1791. *Narrative of the Building of Edystone Lighthouse*. Hughes, London.

Smeaton is widely credited with generating a new interest in hydraulic materials. His book is a landmark even if it has little relevance for Canadian experience.

Vicat, L.J. 1837. *A Practical and Scientific Treatise on Calcareous Mortars and Cements*. Weale, London.
Ranks as a pioneer along with Pasley.

Watson, J. 1922. *Cement and Artificial Stone*. Heffer, Cambridge.

The Royal Engineers put a lot of effort and money into concrete research and for a period were developing an artificial cement for their own use. The following references are the principal articles from the Corps papers and are useful for tracing the evolving use and applications for concrete and training of engineers in its use.

Ardaugh, Lt. 1866. "Report on Concrete Revetments Built at New Haven Fort." *Corps Papers*. New Series 15.

Graham, Lt. Col. 1865. "Experiments on Limes and Cements." *Corps Papers*. New Series 14, p. 155.

MacQuay, Maj. 1874. "Notes on Portland Cement." *Corps Papers*. New Series 22, p. 137.

Scott, Capt. 1857. "Account of a New Cement." *Corps Papers*. New Series 6, p. 143.

_____. 1861. "Manufacture of a New Cement Described." *Corps Papers*. New Series 10, p. 132.

_____. 1862. "Observations on Limes and Cements." *Corps Papers*. New Series 11, p. 15.

VOLUME VI

CONSERVATION OF MATERIALS

1.2

CONCRETE

DETERIORATION AND DEFECTS

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: A. POWTER

CONTENTS

1.0 INTRODUCTION

- 1.1 SCOPE
- 1.2 DEFINITIONS

2.0 FORMS OF CONCRETE

DETERIORATION

- 2.1 CRACKS
- 2.2 SPALLING
- 2.3 DISINTEGRATION
- 2.4 ABRASION
- 2.5 STAINS
- 2.6 EFFLORESCENCE
- 2.7 ETCHING

3.0 CAUSES OF DETERIORATION

- 3.1 MATERIALS USED IN THE ORIGINAL WORK
 - 3.1.1 *Cement*
 - 3.1.2 *Water*
 - 3.1.3 *Aggregate*
 - 3.1.4 *Additives*
- 3.2 BUILDING PRACTICE AND WORKMANSHIP
 - 3.2.1 *Batching and Mixing*
 - 3.2.2 *Transportation and Placement*
 - 3.2.3 *Consolidation and Finishing*
 - 3.2.4 *Curing*
 - 3.2.5 *Building Details*
- 3.3 EFFECTS OF MOISTURE
 - 3.3.1 *Initial Drying Shrinkage*
 - 3.3.2 *Absorption*
 - 3.3.3 *Corrosion of Reinforcement and Metal Fittings*
- 3.4 CHEMICAL EFFECTS
 - 3.4.1 *Acids*
 - 3.4.2 *Sulphates*
 - 3.4.3 *Chlorides*
 - 3.4.4 *Carbonation*
 - 3.4.5 *Leaching*

3.5 TEMPERATURE EFFECTS

- 3.5.1 *Freeze-Thaw Cycles*
- 3.5.2 *Thermal Expansion and Contraction*
- 3.5.3 *Climate During Construction*
- 3.5.4 *Fire*

3.6 PHYSICAL FACTORS

- 3.6.1 *Impact*
- 3.6.2 *Abrasion*
- 3.6.3 *Loads*

4.0 BIBLIOGRAPHY

1.0 INTRODUCTION

Concrete, which has been prepared properly and placed in a well-designed building, is a very durable material with a slow rate of deterioration. However, after 50 to 100 years in service, the effects of a harsh environment and shortcomings in the preparation make some deterioration inevitable.

Concrete deterioration processes can be extremely complex and their identification prior to repair is not always easy. This article will help architects and engineers identify the types of deterioration and defects found in historic concrete structures (built between 1830 and approximately 1925) and increase understanding of deterioration processes. The quality of historic concrete of different periods can vary considerably (as it can today) due to improper construction practices and the misconceptions of designers, concrete chemists and the construction work force, regarding the nature of the material.

1.1 SCOPE

This article is limited to the deterioration and defects of concrete in historic structures built of mass concrete, reinforced concrete, artificial stone, and concrete blocks. Structural defects specific to concrete blocks are primarily masonry problems and are not included here.

Techniques for the repair of historic concrete structures are described in Section 1.3.

1.2 DEFINITIONS

Carbonation: a slow chemical reaction between atmospheric carbon dioxide and cement paste which hardens the exterior surface and reduces its permeability. Carbonation is accompanied by some shrinkage.

Bleeding: an accumulation of water on the fresh concrete surface shortly after it has been placed.

Cement-aggregate Bond: strength of the adhesion of the cement matrix to the individual pieces of aggregate determines the tensile strength of concrete which contains strong aggregates.

Cement-rich Skin: see lamination, segregation and bleeding.

Cold Joint: the point at which two adjacent pours of concrete meet, is the cold joint – the first pour having already set and partially cured. The bond between the two surfaces is weak and will open under stress (see also “lifts”).

Critical Saturation: the level of saturation at which the expansion of freezing will produce stress, leading to damage (Swenson).



*Carbonation: The Carbonized Skin is Evident Here
Some of the cement matrix has been dissolved from the sides of the old crack exposing the aggregate and causing it to widen.*

Drying Shrinkage: reduction in volume of the concrete when some of the water in excess of that required for hydration evaporates from the mass, causes such shrinkage.

Honeycombed Concrete: concrete from which a large part of the cement paste and fine aggregate was removed during pouring, leaves voids of cement-coated large aggregate, caused by poor compaction or leaking formwork. Voids are left in concrete due to failure of the mortar to effectively fill the spaces between the coarse aggregate particles.

Hydration: a complex process involving several simultaneous series of chemical reactions during which the main constituents of cement, the calcium silicates and aluminates, react with water to produce hydrates and numerous other compounds. The fact that the reaction products are insoluble gives concrete its characteristic durability in the presence of water.

Lamination: when a concrete mix segregates, the water, cement and fine material tend to rise and collect at the top of the pour. The result is lamination, the formation of a dense, cement-rich layer of paste at the top of the pour likely to delaminate as a result of thermal or moisture content changes (Feldman 1969).

Lift: the process of removing the formwork from a completed pour of concrete and re-erecting it at a higher level for the next pour; also used historically to refer to one "course" of concrete in place. The "lift lines" are the marks of the formwork and the cold joint between pours.

Natural Hydraulic Cement: the product of burning limestones, which contain sufficient silicious impurities (from three to forty percent), to produce a lime with hydraulic properties. Most of the cements manufactured in Canada between the late 1830s and the late 1880s were of this type.

Portland Cement: the product of burning at approximately 1300°C an artificially prepared mixture of limestone and a source of silicates and aluminates (clays). The resulting clinker is then finely ground.

Ramming: a historic method of consolidating concrete in the form, by pounding with a heavy wood ram until water began to appear at the surface.

Reaction Product: the compounds which are the result of a chemical reaction.

Segregation: separation of the coarse aggregate from the cement, water and fine aggregate caused by gravity or lateral movement of a wet mix or excess vibration.

Vibrating: the current method of consolidating freshly poured concrete in the forms, is by immersing a vibrating head into the concrete.

Water to Cement Ratio: water is needed to wet the surface of the aggregate and to hydrate the cement. All water additional to this is "free water" which increases plasticity and workability, but reduces strength and durability. The ratio of water to cement is the chief factor which controls strength for a given cement content.

2.0 FORMS OF CONCRETE DETERIORATION

The most common forms of concrete deterioration and their causes are described below.

2.1 CRACKS

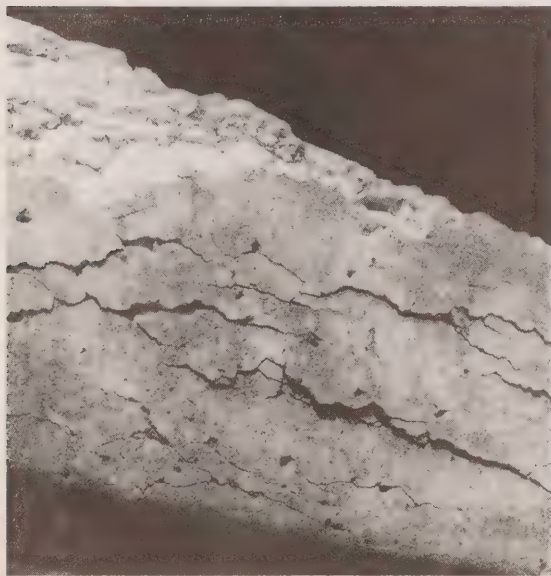
- a. **Crazing** is the term applied to extremely fine cracks arrayed in a random pattern across a surface. They are most visible because of the water they retain when the surface has just dried. These hair-thin cracks penetrate only the immediate surface and are usually caused by differential thermal movement, differential moisture movement, carbonation or alkali silica reaction. Crazing is not a serious form of deterioration, but the cracks do provide openings through which moisture can be drawn by capillarity. Freeze-thaw cycles and the crystallization of de-icing salts can then cause considerable damage to the surface.



Crazing Cracks in a Pavement Slab in the Process of Drying Out (Cordon)

- b. Map cracking is often called alligatoring, after its resemblance to the pattern on an alligator's back. It is similar to crazing, but map cracks are larger and more open. These cracks occur to some depth and are serious, because of the amount of water they let into the concrete.

In historic concrete, map cracks are usually caused by the differential movement, between concrete near the surface and the mass, from the effects of freeze-thaw cycles, internal chemical reactions or volume change of the material below the surface. In some locations, such as retaining walls, the cracks are marked by salt deposits, indicating penetration of soluble salts from ground water or leaching of lime from the cement matrix. Analysis of the salt and the groundwater will determine which is the case.



Advanced Stages of Freezing and Thawing Deterioration (cracking and spalling) in a Parapet Wall

- c. Deterioration line or d-line cracking is another form of pattern crack where the cracks are short and run parallel to a joint or edge of a surface. D-line cracking is usually attributed to freeze-thaw cycles and the vulnerability of edges and corners to wetting. Non-freezing temperature changes have also been

blamed. D-line cracking usually precedes spalling and disintegration at the edge or joint.

Short cracks less regularly patterned than d-line cracking also precede spalling due to freeze-thaw action near a joint, again because of the susceptibility of corners and edges to moisture.

- d. Parallel cracking is the first suggestion of corrosion of reinforcement. These cracks trace the pattern of reinforcement. They open steadily because of internal pressure and rust stains may appear in the area of the crack. As the deterioration continues, the concrete surface on either side of the crack spalls, exposing the steel.
- e. Long, isolated cracks are commonly found in both new and historic concrete structures. Their appearance and characteristics vary depending on the cause. The most likely cause, and the first to consider, is initial drying shrinkage and seasonal temperature fluctuation (Johnson, p. 107). These cracks usually run across slabs or surfaces having no construction or expansion joints. They will occur at some point of restraint, such as an opening or change of section. Both types can be active, and crack widths should be measured periodically through the year.
- f. Structural cracking, unlike shrinkage and temperature cracking, will usually indicate the location and direction of the imposed load which caused the crack. The main danger from cracks, aside from the possibility of structural collapse, is the continued deterioration from moisture penetration (Johnson, p. 66). The locations and directions of the cracks themselves and any dislocations present, can provide the best indication of their cause.
- g. Stress cracking occurs when stress is applied to a plane of weakness in the concrete (for example, construction joints, cold joints, formwork lifts). The two main causes of cracks in this situation are differential expansion and contraction of adjacent pours of differing densities and freezing and thawing of water which has penetrated a poorly bonded cold joint. Freeze-thaw cycles can dislocate adjacent pours once the crack has opened. The location of the cracks themselves usually indicates the cause.



300 mm Concrete Embrasures Splay Destroyed by Pressure of Tree Roots

2.2 SPALLING

Spalling is the detachment of concrete from the surface by internal bursting pressure. Although it is a form of deterioration in its own right, spalling sometimes develops from pattern cracks and can be found along with disintegration. The exposed surface of spalled concrete usually shows no other evidence of deterioration; the cement matrix is sound and the aggregate is firmly anchored in it. The aggregate may be either broken or intact, depending on the strength of the aggregate and the strength of the cement-aggregate bond.

Spalling in historic concrete is usually the result of freeze-thaw cycles and is found in any area subject to freezing temperatures where moisture is present and can penetrate the surface (for example, porous concrete, cracked or crazed areas, wood left in the concrete, or cold joint interfaces). Dense surface layers are particularly susceptible to freeze-thaw spalling. The other significant cause of spalling in historic structures is the internal pressure exerted by rusting metal reinforcement or fittings in the concrete. This cause is usually obvious.

Spalling can have serious implications for a structure. Substantial losses of section and corrosion of reinforcement are common and are matters of considerable structural concern. Even when the stability of the structure is not in doubt, as in large mass gravity structures, spalling detracts from the appearance of a concrete surface.

2.3 DISINTEGRATION

Disintegrating concrete is loose, crumbly and lacks cohesive strength. Disintegration is most often the result of chemical attack or freeze-thaw cycles, when the concrete is of less than ideal quality or the conditions are particularly severe. Freeze-thaw cycles often cause disintegration where water content approaches the critical saturation point, such as at the waterline of marine structures and slabs subject to ponding. Freeze-thaw disintegration is progressive while deep decay indicates that the attack is probably chemical. Disintegrated concrete seldom indicates a superficial problem and requires immediate attention.

2.4 ABRASION

Abraded concrete is readily recognized, as the surface of the damaged area usually reflects the movement and direction of the abrading object or surface – the cement and aggregate are uniformly scored. Abrasion is an external condition only, but can cause substantial loss of material, thereby affecting the structural stability of the member. Abrasion can also expose aggregate and the cement-aggregate interface to the weathering effects of moisture.

2.5 STAINS

The stains usually found on historic concrete are from iron rust, copper, bronze, petroleum oils, bitumen, paint, atmospheric dirt and plants and micro-organisms. Few of these are harmful to the structure, but their removal from the surface may be desirable because of their appearance. Stain removal is difficult because the stains tend to soak into the porous concrete surface. Some stains react chemically with the hydrated cement or the aggregate, making total removal impossible (see Ramachandran and Beaudoin 1979).

2.6 EFFLORESCENCE

Efflorescence generally consists of whitish crystalline deposits of salts on the surface or hard calcareous deposits at crack openings. The causes of efflorescence on historic concrete follow:

- a. Salt-laden groundwater passes through porous or cracked concrete. When the water evaporates, the salts crystallize on the dry surface or just below it in the voids, exerting sufficient internal pressure to spall the surface.

- b. Lime is leached from the cement matrix by soft water percolating slowly through porous or cracked concrete. The leached lime is deposited on the surface at the exit point as powdery white streaks or hard calcareous deposits (stalactites). Leaching leaves the aggregate supported in a silica skeleton which has little strength. Where leaching has been underway for some time, particles of aggregate can be seen in the runoff deposit. The main implication of leaching is that it causes crack openings to widen and results in a general loss of strength.

2.7 ETCHING

The surface of etched concrete is usually eroded in a pattern which traces the water runoff. The depth of damage can be very slight (for example, a slight roughening of the surface) or extremely heavy and channelled. Etching is caused by the reaction of acid in runoff water with the alkali cement. The acid often leaves the aggregate protruding beyond the surface giving it a rough texture. The most common sources of acid are rainwater, especially in industrial areas, and some forms of plant growth, particularly lichens.

Surface erosion by etching is often so slow that its effects are masked by other forms of weathering; however, it can be rapid and should not be ignored as a possible source of deterioration.

3.0 CAUSES OF DETERIORATION

Identification of the cause of concrete deterioration in historic buildings is seldom straightforward. Deterioration is usually the result of several interrelated causes; however their certain identification is not always possible. A single section of historic concrete could be cracked, spalled and on the verge of structural collapse as a result of frost heaving, shrinkage, de-icing salts, a marine location and so on.

3.1 MATERIALS USED IN THE ORIGINAL WORK

In the past, inappropriate or poor quality materials were often used in making concrete because knowledge of concrete chemistry at the time was inadequate. Occasionally these materials can be detected very quickly, but their effect is usually more long term. They can affect the properties of the concrete and its ability to withstand other agents of deterioration.

3.1.1 Cement

Before the late 1880s natural hydraulic cements were extensively used for concrete work in Canada. The concrete made with such cement was usually lighter and more rapid setting than that made with Portland cement, but had lower ultimate strength. The fineness to which the cement was ground determined the rate and degree of hydration and also influenced the ultimate strength.

All cements produce a concrete containing some excess free lime. This lime is soluble in soft water and can be leached out of the concrete, in porous or finely cracked areas, causing loss of strength and eventual disintegration.

3.1.2 Water

Concrete must be mixed with clear water that is free of salts, oil, clay and organic matter. The harmful effects of sulphates (found in very hard water) and chlorides (found in sea water) in concrete mix water has not long been understood, and it is possible that historic concrete, particularly on coastal sites, will contain these impurities. Samples of concrete should be tested for these properties. The presence of sodium chlorides in mix water reduces the ultimate strength of concrete and the effectiveness with which it naturally inhibits the corrosion of ferrous reinforcement (the effects of sulphates are described in 3.4.2 below).

3.1.3 Aggregate

Porous aggregates are susceptible to the bursting effects of freeze-thaw cycles if they are exposed to moisture by a fresh crack or spall in the concrete. This pressure can damage the aggregate or the surrounding cement matrix, whichever is weaker.

Concrete containing cement paste and aggregate that expands and contracts differently during temperature or moisture content fluctuations is also subject to internal stresses and separation along the cement-aggregate interface.

Some aggregates contain minerals that react chemically with cement. The products of these reactions have greater volume than the reactants which cause internal bursting pressure. This becomes evident on the surface with the appearance of a maze of pattern cracks which precedes disintegration. The line of reactant between the cement and the aggregate is evident on core samples examined under a glass. Reactive aggregates usu-

ally become evident within ten years of construction, but it can be a much slower process, taking 50 years or more to appear and seventy years before actual damage occurs.

Concrete mixes made with very sharp aggregates are less workable than mixes with rounded aggregates. Some early builders used sharp aggregate in the belief that it made superior concrete but then added more water to the mix to restore workability. Increasing the water to cement ratio reduces ultimate strength and makes a more porous concrete.

3.1.4 Additives

Adding foreign material to a concrete mix to improve its properties is not new. Clay was sometimes added to make the concrete impermeable. Organic “binders,” such as chopped straw, shavings, manure and leaves were sometimes added, particularly by workers in rural areas well away from engineering supervision. These substances provide built-in planes of weakness in the concrete and act as wicks, transporting moisture into the mass.

Chlorides, particularly sodium chloride, were used as “anti-freeze” to allow winter construction; more recently, calcium chloride has been added to accelerate the setting and curing process. These additives increase the probability of corrosion of reinforcement, reduce ultimate strength, and occasionally aggravate cement-aggregate reactions.

3.2 BUILDING PRACTICE AND WORKMANSHIP

Several aspects of historic concrete construction technology and design contribute directly or indirectly to concrete deterioration. The most common ones and their effects are outlined below.

3.2.1 Batching and Mixing

- a. The use of unwashed aggregate causes a poor cement to aggregate bond;
- b. variations in the mix proportions of adjacent pours causes differential expansion and contraction; and
- c. addition of excess water to improve workability produces a more porous concrete with lower ultimate strength, increasing the risk of segregation of cement.

3.2.2 Transportation and Placement

- a. Excessive vibration or lateral movement in the forms causes separation of the constituent parts of the concrete;
- b. dropping concrete into the forms from a high level causes segregation of aggregate from the cement matrix, and air pockets beneath the reinforcement;
- c. leaking formwork causes honeycombed areas and areas of lower to water-concrete ratio;
- d. the addition of large aggregate (rocks) to the concrete already in the forms causes a poor cement-aggregate bond and planes of weakness; and
- e. migration of water from a fresh pour of concrete to an adjacent pour which has previously set and dried causes a localized area of low water-cement ratio and honeycombing.

3.2.3 Consolidation and Finishing

- a. Excessive ramming, tamping, vibration or finishing, causes bleeding of water, cement and fine aggregates to the top of the pour followed by later delamination of this cement-rich layer; and
- b. shovelling aggregate back from the forms causes concrete to set with a dense cement-rich skin at the form face.

3.2.4 Curing

Exposure to freezing, high temperatures or rapid drying during the curing process affects the strength of the bond achieved between particles of cement and between cement and aggregate. This decreases the ultimate strength of the concrete and reduces its ability to resist the effects of other agents of deterioration, particularly freeze-thaw cycles. The degree of damage depends on the severity of the conditions or the rapidity of drying.

Usually it is not possible to identify this defect in historic concrete without laboratory analysis or microscopic examination. Normally, if concrete is exposed to severe conditions of freezing, high temperatures or rapid drying during curing, it will not survive long enough to be historic.



*Shrinkage Crack in Fort Rodd Hill, BC.
The crack has occurred at an opening in the wall and passed
through the coping as well.*

3.2.5 Building Details

Some design problems which commonly contribute to historic concrete deterioration are:

- a. inadequate water shedding details;
- b. restraint of movement, such as movement resulting from drying shrinkage and temperature-related expansion and contraction;
- c. unprotected cast-in ferrous metal fittings and structural sections; and
- d. lack of bond at construction joints and cold joints.

3.3 EFFECTS OF MOISTURE

3.3.1 Initial Drying Shrinkage

A significant characteristic of concrete is that during curing and hardening, its volume decreases. Generally a high cement content increases the shrinkage and a low water to cement ratio reduces shrinkage. If restrained or concentrated, the stresses caused by drying shrinkage will cause cracking in long walls and roof slabs. Shrinkage cracks are generally

long and regularly spaced, usually at a change of section or opening in the concrete. Reinforcement distributes the stresses of shrinkage; consequently, the cracks tend to be more frequent, but closed. An unreinforced wall might have fewer cracks, but they will probably be wider. Shrinkage cracks are common in historic concrete structures (see Hutcheson).

3.3.2 Absorption

Concrete expands as its moisture content increases and contracts as it decreases. Although this movement is never equal to total drying shrinkage, the amounts can range from 0.01 percent to 0.5 percent, depending on the concrete. If restrained, this movement can cause cracking. Absorption expansion and contraction are most significant in conditions approaching saturation (for example, marine piles, high water table) [Johnson, p. 68].

3.3.3 Corrosion of Reinforcement and Metal Fittings

Concrete provides an ideal environment for the protection of iron or steel from corrosion. Not only is the concrete itself chemically inert in the presence of ferrous metal but also it prevents exposure of the metal to oxygen and water.

If reinforcement or externally mounted metal fittings are exposed to moisture and oxygen by a spall, crack or an area of porous concrete, corrosion of the metal will begin, producing oxides occupying approximately eight times the volume of the parent metal. The resulting stresses will first crack and then spall the adjacent concrete.

The pressure exerted by corroding metal fittings, such as railing posts, hardware and lintels, can be sufficient to burst surrounding concrete and displace adjacent "lifts."

Reinforcement corrosion damage is characterized by surface cracks running parallel to the direction of reinforcement. As this condition deteriorates, the surface concrete spalls from above the reinforcement starting at the mid-diameter of the reinforcement. Surface rust stains usually accompany reinforcement corrosion. Sometimes all the stains appear on the surface before any other evidence of physical damage (Johnson, p. 68).

Calcium chloride or sodium chloride in the concrete can dramatically increase reinforcement corrosion.

3.4 CHEMICAL EFFECTS

Because internal chemical reactions usually begin soon after mixing, they are seldom encountered as a form of deterioration in historic concrete. Most forms of chemical deterioration are external.

3.4.1 *Acids*

Being alkaline, concrete is susceptible to chemical attack by acids. The main sources are acidic rain water in industrial areas, acidic runoff from plants, particularly mosses and lichens, growing on or near the concrete and acidic soils and groundwater.

When acids react with the cement, the soluble reaction products which are produced etch the concrete surface, usually tracing the pattern of water runoff over the surface. The small and large aggregate are left protruding from the cement matrix and will eventually become unsupported.

3.4.2 *Sulphates*

Concrete is susceptible to attack by solutions of sulphate salts, the rate and degree of attack being dependent on the composition and permeability of the cement, presence of water and the amount of sulphate (see Swenson). Sulphates, usually in soil or groundwater, react with some components of the cement paste. The reaction products have a greater volume than the reactants, causing the cement matrix to disintegrate progressively inward from the surface.

3.4.3 *Chlorides*

Deterioration of concrete due to its immersion in sea water was described in detail as early as 1880 and was well known 50 years before that. Concrete in wetting and drying contact with sea water over a long term will suffer from surface deterioration, particularly if the concrete is not of the highest quality. The cement matrix deteriorates through ion exchange leaving the aggregate unaffected, but protruding from the surface of the eroded cement matrix (Feld, p. 118).

3.4.4 *Carbonation*

Fresh cement reacts with atmospheric carbon dioxide at a slow, continuous rate, progressing from the surface inward. The reaction causes the formation of a thin skin on the con-

crete which is more dense and less permeable than the mass of concrete beneath. Under the effects of weather and temperature fluctuations, this skin eventually crazes and cracks admitting moisture. Freeze-thaw cycles will detach the skin from the mass of concrete as a spall. The carbonate skin can be between 5 mm and 25 mm deep, depending on the porosity and age of the concrete.

3.4.5 *Leaching*

Soft water percolating through fine cracks or porous areas of concrete will dissolve minute quantities of lime out of the cement matrix leaving the aggregate supported in a weak silica skeleton. Leaching is characterized by powdery white deposits or "stalactites" at the water exit points. Although not usually dangerous, leaching indicates potential problems from other sources, such as water entry, corroding reinforcement and eventual loss of strength.

3.5 TEMPERATURE EFFECTS

3.5.1 *Freeze-Thaw Cycles*

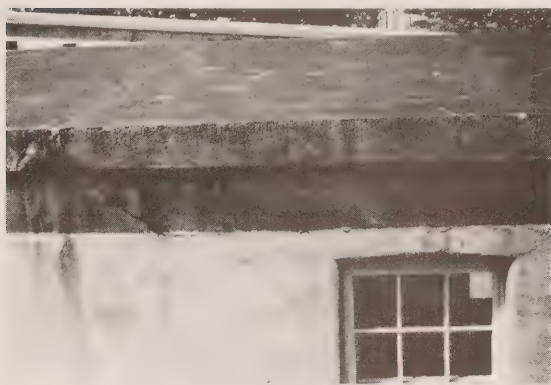
The internal stresses caused by the freezing and thawing of moisture in the voids of a concrete mass are possibly the most significant agents of deterioration of historic concrete.

There are several mechanisms that explain frost damage of concrete. Concrete having a moisture content approaching critical saturation (91 percent) is most vulnerable, but concrete with a lower moisture content can be damaged over time due to the complex patterns of sub-freezing moisture movement and the buildup of hydraulic pressure in some parts of the cement paste (see Swenson). Freeze-thaw damage is usually an aggravation of other conditions occurring most often in areas of porous concrete or aggregate, in poorly drained horizontal surfaces, at corners and edges, near ground level, as a result of poorly designed drainage details or where the density of the surface of the concrete is greater than the density of the mass (Cordon, pp. 23-27).

Freeze-thaw cycles have a more severe effect on concrete when de-icing salts are used. These salts increase the supply of moisture to the concrete from the melting of ice and snow, initiate internal freezing by lowering subsurface temperatures, and cause the deposit and build-up of salt crystals in the voids of the concrete (see Williams).

Deterioration due to freeze-thaw cycles is usually conspicuous and easily recognized as:

- a. scaling and shallow spalling of slabs;
- b. cracking and heavy spalling at corners and angles;
- c. crumbling of the cement paste and exposure of aggregate (common in saturated conditions); and
- d. d-line cracking patterns of short parallel cracks at the edges of slabs.



Common Design for a Roof Slab for Small Buildings in Late 19th Century
Shrinkage and temperature fluctuation stresses are concentrated at the reduction section of concrete over the iron joist causing a crack. Water entry through the crack eventually will begin corrosion of the joist.

3.5.2 Thermal Expansion and Contraction

One of the characteristics of concrete is that it expands when heated and contracts when cooled. If this change in volume is restrained, the resulting stresses will cause the concrete section to crack. A concrete floor slab built late in the summer will experience a temperature drop of 21°C or more which produces a dimensional loss of 12 mm per 30 m (Johnson, p. 64). Temperature cracks are common:

- a. in floor slabs or retaining walls which have no expansion joints;
- b. at the intersection of two adjacent concrete surfaces;
- c. where a change in the dimensions of the concrete section causes differential expansion and contraction between the two elements; and
- d. where concretes of slightly varying density meet with a cold joint.

3.5.3 Climate During Construction

Concrete exposed to extremes of heat or cold while it is still plastic and curing will suffer strength losses of 50 percent or more and will generally be porous and not durable. Less extreme conditions can still result in concrete of low ultimate strength.

3.5.4 Fire

Exposure to high temperatures causes chemical changes in the component parts of concrete which affect its strength and thermal properties. The heat of fire drives off moisture held in the pores of the concrete and dehydrates the calcium silicate hydrate (tobermorite gel) and the calcium hydroxide. This process retards the flow of heat through the concrete, but also results in strength loss.

3.6 PHYSICAL FACTORS

3.6.1 Impact

The first significant developments in understanding the effects of impact on concrete stemmed from British, Belgian and German research for trench fortifications during the First World War.

As concrete is a heterogeneous material, it is subject to internal and external damage from shock waves due to impact. Shock both disintegrates and spalls concrete structures because the aggregate, cement matrix and reinforcement transmit the shock waves at different rates. Piers, fortifications and heavy machinery foundations are exposed to the effects of impact shock.

3.6.2 Abrasion

Unlike impact, abrasion is the gradual removal of material from the surface by direct friction and contact with another object or surface. Abraded surfaces are usually obvious, as their appearance reflects the movement and direction of the abrading object and both the aggregate and cement matrix are uniformly scored. The location of the damage in relation to traffic is another indicator. The commonly encountered agents of concrete abrasion are vehicles, foot traffic, ships, mooring ropes, floating ice and high velocity water (Johnson, pp. 84-86).

3.6.3 *Loads*

Creep is a characteristic by which concrete under constant stress continues to deform over a considerable length of time (Nelson, p. 18). The deformation increases at a declining rate (75 percent of 20-year creep occurs in the first year). If the load is removed there is some recovery but creep is not reversible. The effect of creep on the strength of a beam is not significant, but the increase in deformation can result in transfer of loads to other members such as walls or partitions.

Other ways in which loads cause structural deterioration are:

- a. increased dead or live load beyond designed capacity through additions or changes in use;
- b. unanticipated loads such as earth tremors;
- c. reduction of load-bearing capacity by other forms of deterioration; and
- d. differential settlement of foundation supports.

These types of deterioration are characterized by deformations and cracks.

4.0 BIBLIOGRAPHY

American Concrete Institute. 1975. "Durability of Concrete," *ACI Journal*. Detroit.

_____. 1977. "Guide to Durable Concrete," *ACI Journal* (December). Detroit.

Canadian Portland Cement Association. n.d. *Design and Control of Concrete Mixtures*. Ottawa.

Cordon, W.A. 1966. *Freezing and Thawing of Concrete Mechanisms and Control*. ACI, Detroit.

Feld, J. 1964. *Lessons from Failures of Concrete Structures*. American Concrete Institute and Iowa State University, Detroit and Ames, IA.

Feldman, R.F. 1969. *Volume Change and Creep of Concrete*. Canadian Building Digest No. 119. National Research Council, Ottawa.

Harmathy, T. Z., and L. W. Allen. 1971. *Thermal Performance of Concrete Masonry Walls in Fire*. Canadian Building Digest No. 140. National Research Council, Ottawa.

Hutcheson, H.B. 1961. *Concrete*. Canadian Building Digest No. 15. National Research Council, Ottawa.

Johnson, S.M. 1965. *Deterioration, Maintenance and Repair of Structures*. McGraw-Hill, New York.

Lea, Sir F. n.d. *Chemistry of Cement and Concrete*. London.

Nelson, H. 1976. *A Selection of Historic American Papers on Concrete-1876-1976*. ACI, Detroit.

Ramachandran, V.S., and J. Beaudoin. 1979. *Removal of Stains from Concrete Surfaces*. Canadian Building Digest No. 153. National Research Council, Ottawa.

Swenson, E.G. 1969. *Durability of Concrete Under Winter Conditions*. Canadian Building Digest No. 116. National Research Council, Ottawa.

_____. 1971. *Concrete in Sulphate Environments*. Canadian Building Digest No. 136. National Research Council, Ottawa.

_____. 1972. *Portland Cement in Building Construction*. Canadian Building Digest No. 145. National Research Council, Ottawa.

Williams, G.P. 1977. *Chemicals for Snow and Ice Control Around Buildings*. Canadian Building Digest No. 191. National Research Council, Ottawa.

Illustrations are the property of the Heritage Conservation Program, unless otherwise noted.

VOLUME VI

CONSERVATION OF MATERIALS

1.3

CONCRETE

CONSOLIDATION AND REPAIR

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: A. POWTER

CONTENTS

1.0 INTRODUCTION

- 1.1 BACKGROUND
- 1.2 DEFINITIONS

2.0 GENERAL CONSIDERATIONS

3.0 INVESTIGATIVE TOOLS AND REPAIR MATERIALS

- 3.1 INVESTIGATIVE TOOLS
- 3.2 REPAIR MATERIALS

4.0 REPAIR OF CRACKS

- 4.1 GENERAL CONSIDERATIONS
- 4.2 CRACK INJECTION AND GROUTING
- 4.3 SEALING
- 4.4 BLANKETING
- 4.5 MEMBRANES
- 4.6 STITCHING
- 4.7 EXTERNAL STRESSING
- 4.8 AUTOGENOUS HEALING

5.0 REPAIR OF SPALLED AND DISINTEGRATED CONCRETE

- 5.1 GENERAL CONSIDERATIONS
- 5.2 SURFACE PREPARATION
- 5.3 COMPATIBLE MATERIALS
- 5.4 PATCHING
- 5.5 RECASTING
- 5.6 PNEUMATICALLY APPLIED CONCRETE
- 5.7 CONSOLIDATION
- 5.8 METAL FITTINGS EMBEDDED
IN CONCRETE

6.0 CONTROL OF MOISTURE AND WATER

- 6.1 MEMBRANES AND OVERLAYS
- 6.2 COATINGS
- 6.3 DRAINS AND BARRIERS

7.0 CLEANING AND STAIN REMOVAL

- 7.1 POULTICING
- 7.2 METALLIC STAINS
- 7.3 OIL
- 7.4 BITUMEN AND ASPHALT
- 7.5 PAINT
- 7.6 ALGAE, LICHENS, MOSSES AND MILDEW
- 7.7 GENERAL CLEANING

8.0 ASSOCIATIONS AND SUPPLIERS

- 8.1 ASSOCIATIONS
- 8.2 SUPPLIERS

9.0 BIBLIOGRAPHY

1.0 INTRODUCTION

This article describes the principal techniques for cleaning and repairing deteriorated or defective concrete. It is intended to guide administrators, engineers and architects in the selection of a repair method for historic concrete; and to assist engineers and architects in the design, specification, execution and supervision of repair methods for historic concrete, in conjunction with the reference material and manufacturer's literature.

1.1 BACKGROUND

Included within the historic structures for which the Canadian Parks Service (CPS) has responsibility are many that have concrete as the primary or secondary material. Most of these are military fortifications, including barracks, walls, gun emplacements and canals constructed between the late 1820s and the 1940s.

Because of their special characteristics, historic concrete structures present deterioration problems that are not found in modern concrete structures.

- a. Before 1900, concrete often was not reinforced or reinforced with an unconventional material.
- b. Before 1900, concrete might have been based on a cement other than Portland.
- c. In the late 19th century, concrete construction technology was in its infancy and inappropriate practices were inevitable.
- d. Structures were probably designed to engineering standards unlike those of today.
- e. The deterioration of concrete, which remained essentially sound and cohesive for 75 years or more before requiring repair, is quite different from that of new concrete which requires repair after a very short period in service.
- f. Quality control and supervision varied enormously even within the confines of available knowledge.
- g. Military engineers often anticipated rapid technological change in their field which would render their structures obsolete and, therefore, omitted expensive details that might have prevented some forms of deterioration.
- h. The criteria for what constitutes an acceptable repair for a historic structure will often be unlike those for a modern structure.



Deteriorating Concrete Wall

1.2 DEFINITIONS

Active Cracks: cracks that open and close, usually due to changing environmental conditions.

Bonding Medium: material used to bond fresh concrete to existing concrete.

Compatible Materials: materials that have similar characteristics of expansion and contraction under changing environmental conditions.

Dormant Cracks: cracks that do not move.

Elastic Sealant: a sealing material that returns to its original shape when not under stress.

Mastic Sealant: a sealing material that can tolerate small amounts of movement but will not lose its original shape when under stress. Mastics are generally less expensive than elastic sealants.

2.0 GENERAL CONSIDERATIONS

Techniques for conserving historic concrete structures have advanced a great deal in recent years because of the repair requirements of the United States interstate highway system and other large civil works. Modern techniques are often based on the use of non-cementitious materials acting as bonding mediums, chemical binders, strengtheners, consolidants and admixtures such as plasticizers. These materials primarily provide effective structural repair quickly; aesthetic considerations are secondary.

Because such techniques are relatively new and have not been the subject of long-term experimentation and evaluation, common sense and compromise should be used in selecting a technique and deciding on the extent of work. A suggested selection procedure is outlined below:

- a. Assess the damage including:
 - the depth, extent and rate of deterioration
 - the condition of the concrete in high-stress areas
 - the condition (or existence) of reinforcing steel
 - the effect of moisture
- b. Before selecting a repair method:
 - consider the performance required of the repair
 - bear in mind that repaired concrete may not be as sound as a monolithic mass of concrete
 - remember that, in all repairs, shrinkage must be minimized, compatible materials used and workmanship must be of the highest standard
 - consider a policy of non-intervention, monitoring, preventive maintenance and judicious neglect (for example, clearing out drains, overgrowth and debris).
- c. Test all techniques and mixes before carrying out a repair.

3.0 INVESTIGATIVE TOOLS AND REPAIR MATERIALS

3.1 INVESTIGATIVE TOOLS

The following tools are useful for investigating historic concrete:

a. Soniscope :

An instrument used to measure the travel time of an ultrasonic pulse through concrete to establish its compressive strength and degree of uniformity in quality, to determine the effect of freeze-thaw action and to detect cracks.

b. Core drill:

A tool used to remove a sample (core) of the concrete at depth. The sample may be tested for strength, unit weight, approximate mix proportions and cement content.

c. Rebound hammer:

An instrument that can indicate concrete strength by measuring rebound. However, it is of limited use on historic concrete structures: it will indicate concrete strength to within 15 percent accuracy, but only on specimens cast and cured under conditions for which calibration curves have been established (see Feldman).

d. Telltales:

Any of several devices designed to reveal whether cracks are active or dormant. Simple telltales, such as plates of glass, will show only that movement exists, whereas precisely located bronze pins can be used to measure the exact movement across the crack.



Telltale

- e. Strain gauge:
An instrument designed to measure the stress carried at a point of a structural member or across a fracture.
- f. Photographs:
Pictures help to determine the rate of deterioration, if they have been taken over a period of years. Use them in conjunction with careful inspection of the concrete.
- g. Records:
Inspections and recording may identify sources of raw materials, special foundation conditions, mixing and placement methods, presence of reinforcement or proportions of the original mix.

3.2 REPAIR MATERIALS

There are many concrete repair products on the market, most of which are based on epoxy or cement. Request and examine the manufacturer's full literature and field-test data before making a final selection.

- a. Cement:
Cement can be used for the following:
 - recasting (when mixed with suitable aggregate)
 - grouting (when mixed with water)
 - sealing reinforcement (when mixed with latex or other additives)
 - as a bonding agent for patch repairs.

Cement sold under the trade names *Gunit* and *Shotcrete* is suitable for pneumatic application.

It is seldom feasible or possible to reproduce a historic cement. Consequently, it is normal to use ordinary Portland cement blended with white cement for a colour match, and proportioned with aggregate and water to produce a repair medium with suitable strength and density characteristics.

- b. Aggregates:
Aggregates are used in the normal manner for new work. Careful selection and grading of aggregate will help achieve a satisfactory texture and colour match with existing material. The aggregate binders most often used are cement, cement and latex, and epoxies.
- c. Metals:
Metals are used for reinforcement, "density"-type repairs and the keying-in of patches.

The principal metals are copper, phosphor-bronze, stainless steel and mild steel. Non-ferrous metals are used for stitches and armatures or where minimal concrete cover is unavoidable. Conventional mild steel reinforcement is used for external tensile stressing and reinforcing large areas of recasting.

- d. Sealants:
There are two types of sealants. Crack sealants stop the passage of water into cracks in the concrete. Surface sealers prevent water from penetrating into porous concrete. The most commonly used surface sealers are bitumen, mastic asphalt, paint, linseed oil, silicones, epoxies and latex-based materials.
- e. Organic polymers:
Organic polymers are used to repair cracks, bind or bond patches and coat steel reinforcement. Low-viscosity epoxies are preferred, because they shrink less on hardening and will bond to damp concrete. They are available in a wide range of products from a number of manufacturers (see 8.0 below).
- f. Membranes:
Membranes are surface-sealing materials in the form of impermeable roll sheeting such as tar and felt built-up roofing, PVC sheet, bitumen-impregnated fibreglass and butyl rubber. As the individual properties of these materials vary considerably, consult the manufacturer's literature and particularly the field test data on these products.
- g. Admixtures:
Admixtures or air entrainers, expanders, retarders, accelerators and water reducers can play an important role in conservation. In some cases, they will improve the quality of the repair medium, alter its physical characteristics, reduce shrinkage and increase its frost resistance. Admixtures should enhance good workmanship, not be a substitute for it.

4.0 REPAIR OF CRACKS

4.1 GENERAL CONSIDERATIONS

When a concrete structure has cracked, it does not necessarily mean that the structure has failed; this is particularly true of

historic structures. The real danger of cracks is usually from the water they admit into the concrete mass.

Building owners usually repair a crack for the following reasons:

- a. to conceal it;
- b. to prevent penetration of water into the building;
- c. to prevent water from washing lime from the cement;
- d. to prevent corrosion of reinforcement; and
- e. to restore structural continuity.

If a crack does not require repair for one of the above reasons, it is better to leave it alone.

When considering a crack repair method, try to pinpoint the cause of the crack (see Section 1.2 "Concrete: Deterioration and Defects"). Then, using telltales or some other measuring device (see 3.1, d. and e. above), determine whether the crack is active or dormant and the extent of movement.

In most cases, the cause and state of activity of the crack will determine the repair method used.

If a crack is subject to hydraulic pressure, the repair will more effectively prevent the passage of water if it is placed on the pressure face.

Steel reinforcement must be cleaned of all scale and rust and brushed with a protective coating of two parts cement and one part latex or styrene butadiene. This treatment protects the steel from further corrosion and improves the concrete-steel bond.

4.2 CRACK INJECTION AND GROUTING

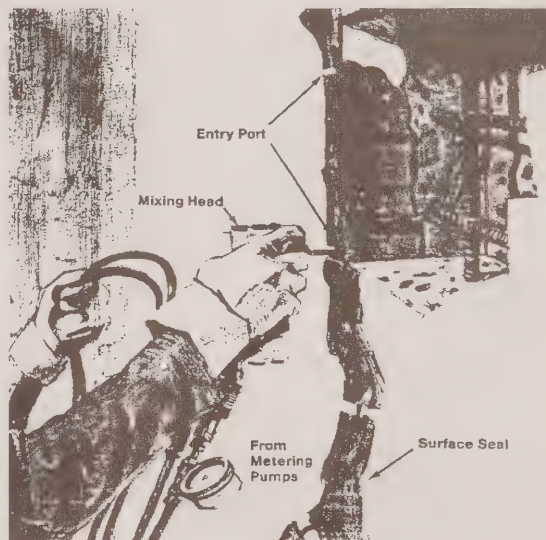
Cracks, particularly dormant ones, can be filled and bonded by injecting the entire depth with an epoxy bonding compound or cement grout. If the crack is slightly active, a low modulus epoxy may be used, although a low-viscosity epoxy is preferred because it bonds to damp concrete and has a wide temperature range and low shrinkage.

The procedure is as follows:

- a. Flush debris and dirt out of the crack with water, a solvent, or compressed air; allow the surfaces to dry.
- b. Locate the injection points along the crack and drill, screw, or fix the nipples into place. The injection points should be as far apart as the crack is deep.
- c. Seal the remaining face of the crack with an epoxy gel, latex-cement mortar or clay.
- d. If a permanent glossy appearance is objectionable, brush a strippable plastic along the crack.

- e. Protect the adjacent face of the concrete with masking tape.
- f. Back seal if the crack extends completely through the concrete mass.
- g. Inject the adhesive into the first, lowest port until it appears at the next port.
- h. Plug the first port and begin injection at the second port. Repeat until the entire crack in the concrete is filled.

Adhesive can be forced into the crack in several ways. Small cracks can be filled using a caulking gun and rubber tube; larger ones, with a powered pumping system. This equipment can develop pressures up to 2000 kPa, although pressures above 650 kPa are seldom required. For fine cracks, low pressure injection is preferred to force the epoxy well back into the crack.



*Full-depth Injection of Epoxy into Cracks by Metered Pumps
Courtesy of Adhesives Engineering Co.*

After the epoxy has cured, the surface seal is removed, leaving the trace outline of the crack. Some references suggest routing the crack opening to 5 mm wide before injection. This stiffens the temporary surface seal, allowing the operator to use a higher injection pressure, but the resulting repair is visually more

obtrusive. Although cracks repaired in this way can be inconspicuous, it is advisable to keep the adhesive well back from the face of the concrete by pressing the temporary surface seal a short way into the crack. A clay surface seal is best for this technique (see trade literature by Sika Chemical of Canada and Adhesives Engineering Company).

Grouting is similar to epoxy injection in procedure, application and limitations, but the repair medium is based on cement. Cement grouting is a comparable alternative to epoxy injection where fire resistance or cold weather working conditions must be considered. However, it gives a very brittle repair unsuitable for active cracks.

Where cracks are reasonably straight, an alternative to normal grouting is to form a key by drilling a 50-75 mm hole down the length of the crack. After placing a surface seal along the crack, a grout of high-early-strength Portland cement is poured into the drill hole and crack. The cement key formed by the drill hole will prevent transverse movement and reduce the flow of water through the crack. If a better water seal is required, the hole can be filled with an elastic sealant or a pre-cast concrete key, set on an isolating membrane (see illustration).

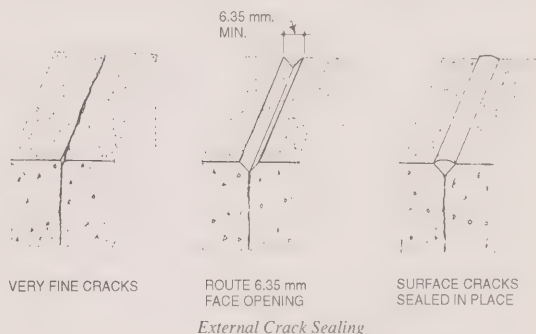
4.3 SEALING

Sealing is probably the simplest, most common technique for dealing with both fine and large or dormant and slightly active cracks. Those subject to hydrostatic pressure must be sealed. Unlike injection and grouting, sealing does not involve filling or bonding. To prevent water entry, the crack is simply covered at the surface, usually with epoxy, latex emulsion, mortar grout, commercial hot-pour joint sealer and hot tar (depending on the effectiveness and permanence required and the characteristics of the crack).

The following procedure is similar for each sealant:

- For cracks too narrow to allow the sealant to enter, the path of the crack should be routed or lightly worked with a cold chisel to approximately 6 mm.
- Ensure that all surfaces are clean, dry and free of all loose material.
- Apply the sealer as directed by the manufacturer.
- If a latex-cement grout is used, mix two parts colour-matched Portland cement and two parts styrene butadiene latex by weight.

- With a brush or squeeze bottle, apply the grout in two coats, one to two weeks apart. If the repair is not on an exposed surface, brush the grout to 75 mm of each side of the crack.
- If an epoxy sealer is used, prime the surfaces with a suitable primer. Apply the epoxy sealer with a caulking gun, trowel or squeeze bottle or pour it directly from the can, depending on the orientation of the crack and consistency of the epoxy. The edges of the crack can be masked with masking tape (see Johnson; Champion; Perkins and trade literature).

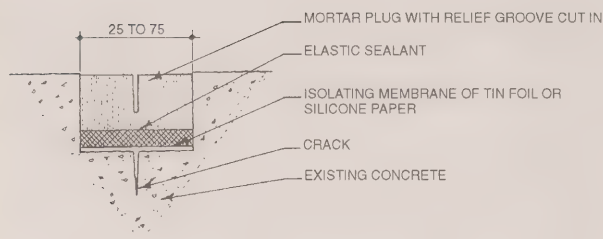


4.4 BLANKETING

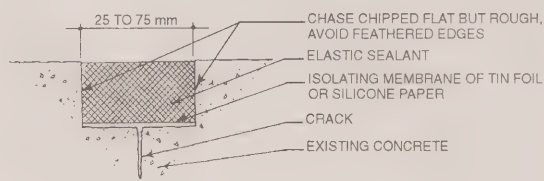
This method of repair is similar to sealing except that it is a larger, more sophisticated form of repair and can be used for cracks that are active, dormant or subject to internal hydraulic pressure (but not subject to bending or shear stresses). Blanketed cracks tend to be visually obtrusive, which makes them unsuitable for certain applications.

The usual method is to form a chase along the crack placing an *elastic* or *mastic sealant* at the bottom. The sealant used will be determined by the movement characteristics of the crack.

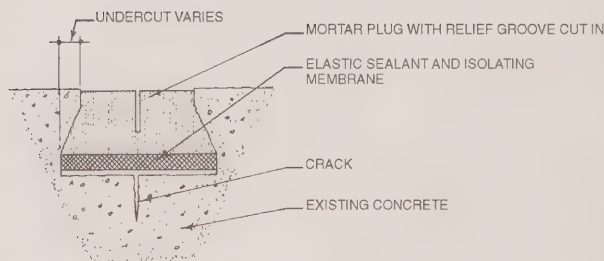
The sealant should be prevented from bonding with the bottom of an active crack by installing a silicone-paper bond breaker. The configuration of the chase will be determined by the characteristics of the sealant (width normally can be expected to be four to six times anticipated movement, and depth, a minimum of 20 mm). The strength and elastic properties of the sealant should be checked with the manufacturer. If the repair must resist internal hydraulic pressure, the chase is undercut and a mortar plug installed over the sealant. Blanketing is an expensive method of repair requiring a high level of workmanship.



FOR TRAFFIC BEARING SURFACES



FOR ACTIVE CRACKS



FOR REPAIRS AGAINST INTERNAL HYDROSTATIC PRESSURE

Three Types of Blanket Repair

4.5 MEMBRANES

Sheet membranes can be used to seal large areas of porous concrete or concrete containing many cracks, as described in 6.1 below.

4.6 STITCHING

Tensile strength can be restored to concrete by placing a series of non-ferrous stitches or “dogs” across a crack in the fashion of a masonry clamp or timber flitch plate. Before stitches are installed, cracks should be sealed and action taken to reduce the tensile stress that caused them. Then, stitches of varying lengths (300 mm to 900 mm to distribute the tensile load) should be placed on both sides of each crack. Total

tensile strength of the stitches must equal the tensile strength of the concrete and any existing reinforcement. Stitches will not resist compressive forces. Although stitches are conspicuous and unsightly, they can be recessed and covered with a matching, properly bonded, non-shrinking mortar patch.

4.7 EXTERNAL STRESSING

External stressing is a way of removing tensile stresses that have caused concrete members to crack under applied loads. In principle, it is similar to stitching, except that an external tensile member is installed to apply compression to the crack to push it back together. Compression forces can also be applied to strategic points in arches by using expanding mortars, jacking and grouting or by wedging. This technique is described further in Johnson.

4.8 AUTOGENOUS HEALING

Freshly cracked concrete can heal itself and recover some tensile strength if the crack is saturated soon after the crack occurs (by submersion or ponding) and has no flow of water through it. The chemical crystallization and bonding process will only occur, however, if the crack is dormant. The significance of autogenous healing for historic concrete lies in the possibility that a visible crack, caused by shrinkage or some incident during construction, might have healed itself soon after its occurrence and may not require further repair.

5.0 REPAIR OF SPALLED AND DISINTEGRATED CONCRETE

5.1 GENERAL CONSIDERATIONS

Because concrete does not bond readily to itself and shrinks as it dries, spalled and disintegrated concrete is very difficult to repair. These shortcomings are compounded by the aesthetic problem of inserting a repair (patch) in a monolithic concrete mass.

Satisfactory repairs can be achieved if an effort is made to get the best possible bond between the repair and the substrate and if the density, colour, aggregate, and surface texture are closely matched to the existing concrete.

5.2 SURFACE PREPARATION

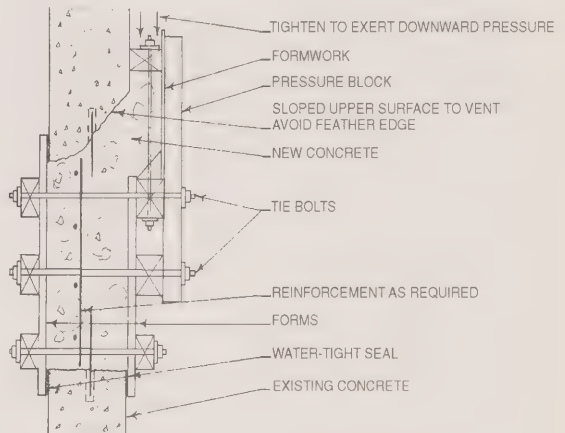
When attaching any new material to old concrete, correct, careful preparation of the surface is essential. All friable, porous or damaged concrete should be removed until sound concrete is reached. Cut back a minimum of 40 mm by means of pneumatic chisels or a high-pressure (20 to 60 MPa) water lance. Drilling 50 mm holes 200-300 mm apart to the required depth will sometimes make this task easier.

If reinforcement is encountered, remove enough concrete so that the reinforcement will be encased in the new matrix. This helps to ensure a better key. It is not good practice to have a joint between new and old materials right at the plane of reinforcement.

The edge of the area being repaired should be cut sharp and deep, not feathered, as the feather edge will always crack. A straight saw cut is sufficient for large patches, but small

patches should be undercut or otherwise keyed in place. If non-ferrous metal armatures are used, fix them into drilled holes with epoxy. Top edges of patches on vertical surfaces should slope down and back to prevent an air pocket forming at the top. Repairs that extend to corners or edges should wrap around them.

Within a few hours before making the repair, cut-back surfaces should be rinsed, sandblasted, re-rinsed and brushed to remove any oil or loose material on the bonding surface because they will prevent a good bond (see Johnson; Perkins and trade literature).



Pressurized Formwork for Recasting Sections of Vertical Walls

5.3 COMPATIBLE MATERIALS

A patch repair on a historic concrete structure must have mechanical properties and visual characteristics compatible with the old concrete. Repairs made with incompatible materials eventually will separate from the substrate under conditions of differential contraction and expansion. Where possible, the repair material should match the type of cement, type and grade of aggregate, mix proportions and water-to-cement ratio of the original. This will ensure that the repair and substrate have similar thermal properties, density, permeability and shrinkage characteristics. Despite the fact that there are constant changes in concrete over time—shrinkage, hydration and colour variation, this aging process cannot be duplicated.

A properly matched, aesthetically acceptable repair can only be achieved by a skilled craftsman carrying out experiments at the site. This type of work is of the calibre of a

handicraft and it should not be assumed that just any contractor can achieve a satisfactory result through the use of stock formulae and estimates.

Colour can be matched by mixing standard and white Portland cement and by using the same type and grade of aggregate as in the existing concrete. Matching surface texture is more difficult. Again, the grade and sharpness of the aggregate are important if it is to be exposed. One technique is to oversize the repair slightly, then brush or wash back to expose the aggregate. Other modern techniques of concrete finishing will also prove useful.

Modern analytical techniques can provide some of the information necessary to achieve a compatible repair material. Architects and engineers normally cannot analyse cement and concrete for themselves. The chemistry and behaviour of cement are not yet fully understood and most diagnostic procedures involve sophisticated analytical techniques. Even then, the results can be imprecise. However, with a little practice and a sensitive eye, conservators can glean some information from a concrete sample. This information, however, is approximate and should not be considered a substitute for proper analysis by a laboratory which specializes in this type of work.

Visual examination of a fractured concrete surface will reveal voids or pores. They can be interpreted as follows:

Observation	Interpretations
Small, spherical, bubble-like holes with smooth surfaces	Mix rather wet
Numerous irregular voids	Mix too dry, mix insufficiently compacted, or both
Broken aggregate	Weak aggregate or strong cement-aggregate bond
Aggregate pulled out	Strong aggregate or weak cement-aggregate bond

It is possible to estimate the size and grading of aggregate and the area occupied by the cement paste. The quality of the aggregate and the strength of its bond with the cement can also be determined. The use of a hand lens (x10 power) will help to ascertain more information about the distribution of air voids and any chemical reaction between the aggregate and cement matrix. Laboratory examination with a x50 microscope of a properly sawn, ground sample will clearly show evidence of any chemical reaction between aggregate and cement and the quality of the cement-aggregate bond. A qualified cement chemist can use his or her experience and sophisticated analytical techniques to determine the following about the properties of a sample of historic concrete:

- crushing strength and permeability, both important for the design of a matching or repair mix;
- identity of the cement (the chemist can identify the presence of Portland cement in a sample, but a more precise identification is unlikely);
- mineral composition of the aggregate, also important for the design of a matching mix;
- grading of the aggregate;
- original cement content and volume of cement paste in the sample; and
- original water to cement ratio (this technique, however, is both difficult and expensive).

Those considering professional analysis should be aware that it involves complex, expensive, but still not unreliable procedures. Unfortunately, laboratory analysis is not able to determine several factors affecting the properties of the concrete, such as the detailed composition of a non-Portland type cement and the conditions on the day of construction (for example, temperature and rainfall). All are important to the production of a fully compatible repair medium (Johnson; National Boring and Sounding Co.; personal communication and trade literature).

5.4 PATCHING

Patching is most suitable for repairing small areas of concrete that are otherwise sound. The deterioration could be due to spalling, abrasion or a physical impact. The fact that the concrete is otherwise sound is important; there is little use in applying patches to poor quality material that will require patching regularly.

Patching materials are usually either a compatible and matching mix of cement concrete or a matching aggregate with an epoxy binder.

There are two means of bonding the repair material to the substrate – with cement paste or an epoxy bonding agent.

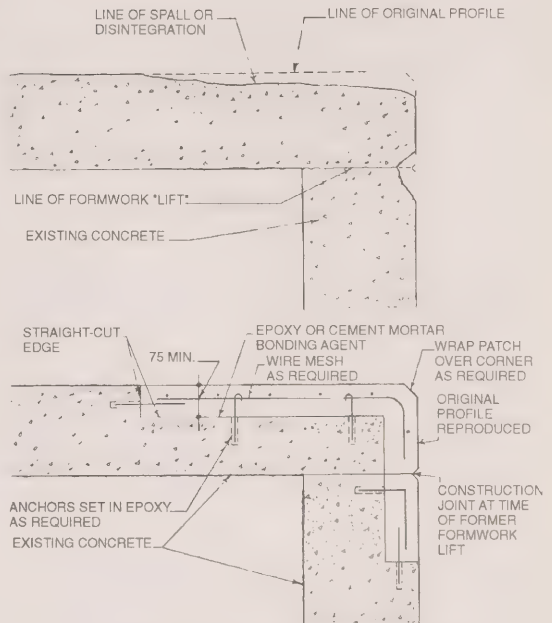
If cement paste is to be used, prepare the surface as described in 5.2 above and saturate the cut-back surface with water, at least ten hours before making the repair, by spraying or covering with wet burlap. A few hours before repair work begins, allow the surface to start to dry. Just before the surface is dry, scrub on a 3 mm (maximum) thick slush coat of mortar of the same cement paste to be used in the repair. Place the patching concrete immediately, tamp and finish the surface with a wooden float, brush or other tool to suit the existing finish.

To minimize shrinkage, the repair material should contain the right quantities of cement, a clean, stable aggregate of which the maximum size is as large as possible (allowing a lower water to cement ratio) and appropriate admixtures in the correct quantities. Keep the surface of the repair damp to ensure proper, constant curing.

If an epoxy bonding agent is used, the procedure is as described above except that the repaired area must be dry, not saturated. The epoxy bonding agent is applied by brush or roller (spray for large areas) and the patch medium placed immediately. Where extra strength is necessary, as in repairs with thin sections, epoxies replace cement as the binder. When epoxy binders are used, the aggregate should be dry (see Johnson; Perkins and trade literature).

5.5 RECASTING

Recasting consists of replacing deteriorated or missing concrete with new concrete placed in the conventional manner. It probably provides the most durable, reliable form of repair and so is particularly applicable where watertightness is required. When large surfaces or sections of heavy structure are severely spalled or have disintegrated, reconstruction by recasting is the only reasonable means of repair (except where interference with historic fabric cannot be accepted). It permits the new section to be made with a higher quality concrete and minor details of construction can be adjusted to give a more durable result. In most circumstances, replacing inferior quality material with equally inferior quality material cannot be justified.



*Replacing Deteriorated Concrete with New Material
Note the repeat of the construction joint.*

There are two main conditions, each of which requires somewhat different treatment:

- a. The repair is large in area but thin in section (for example, a roof slab). In this case, the compatibility of the materials is important to prevent the repair from separating along the interface of the existing material and the repair.
- b. The section of the repair is deep or confined by existing concrete (for example, bridge abutment). Because the stress caused by temperature and moisture change is not great, compatibility of the two materials is less crucial. Large aggregate, a minimum water to cement ratio and air entrainment are advised, to keep shrinkage to a minimum.

In both cases, surfaces to receive new concrete should be prepared as described in 5.2 above, and all corroded reinforcement cleaned and primed with a cement-latex grout. When cutting back old concrete, do so to the next lift or construction joint, particularly if the joint was forced open by freeze-thaw cycles.

Formwork for recasting requires no special features, although to prevent leaks it should be watertight and gasketed where it meets existing concrete. Forms, which cannot be open at the top (for example, when patching a section part way up a vertical wall) should allow for pressure to be applied to the concrete to "force-fit" the repair in place.

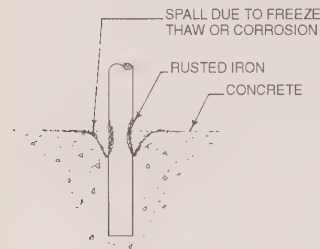
5.6 PNEUMATICALLY APPLIED CONCRETE

Deteriorated concrete on vertical walls can be repaired successfully with pneumatically applied concrete such as *Gunitite*

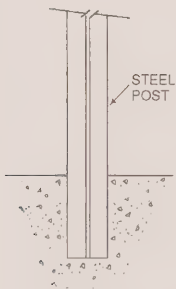
or *Shotcrete*. Care must be taken to allow for expansion and contraction of structures, where necessary, and to achieve an acceptable finish.

5.7 CONSOLIDATION

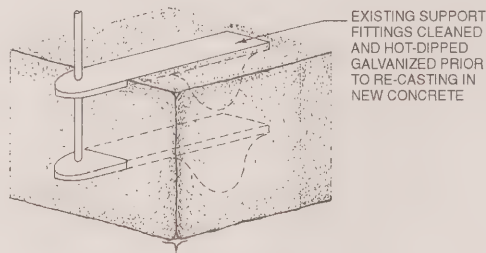
Consolidation stabilizes friable concrete in its "as-found" condition to prevent further decay. Its application to most historic concrete structures is probably limited to a few small details such as doorway mouldings, date stones and moulded features.



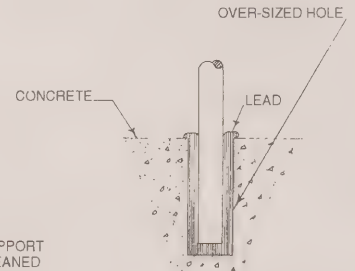
IRON RAILING EMBEDDED IN CONCRETE



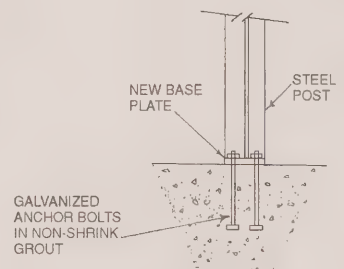
ORIGINAL DETAIL RAILING POST EMBEDDED IN CONCRETE



EMBEDDED DETAIL OF IRON RAILING SUPPORT



NEW RAILING PROPERLY PAINTED AND PLACED IN AN OVER-SIZED HOLE IN STAVED LEAD



NEW DETAIL RAILING POST, SURFACE MOUNTED

Metal Fittings Embedded in Concrete (see Section 5.8)

Consolidants work by depositing an agent in the pores of the concrete which cements the loosely bound material together. Depending on the chemistry involved, there are two main materials:

- a. inorganic materials that induce the precipitation of insoluble ethyl-silicates, carbonates, or silanes inside the pores of the material; and
- b. organic materials that are based on impregnation with synthetic resins, mainly epoxies and silicones.

The advantages and disadvantages of the two are well balanced so that one cannot be recommended over the other. These materials have been used extensively in masonry consolidation projects in Europe, particularly in Germany. Consult trade literature and field test data to determine the product and process best suited to the problem at hand. See 8.0 and 9.0 below for literature and suppliers respectively.

5.8 METAL FITTINGS EMBEDDED IN CONCRETE

Nineteenth century and early 20th-century concrete structures, particularly fortifications, often contain steel or iron fittings embedded directly in the concrete without protection from water penetration. Corrosion of the metal and spalling of the concrete are common in such cases. Several techniques can be used to correct or improve the detail during repair of the spall:

- a. remove, clean, and coat the metal in contact with the concrete, as described in 4.2 above;
- b. seat the metal fitting properly in an oversized hole lined with staved lead;
- c. coat the fitting with zinc by hot-dipping; this will not prevent spalling due to freeze-thaw action, but will prevent rusting;
- d. paint the metal;
- e. relocate the metal fitting itself, if possible; and
- f. alter the connection from an embedded to a bolt-on detail.

(See illustration p. 10)

6.0 CONTROL OF MOISTURE AND WATER

An absolutely dry subterranean space is virtually impossible, but water infiltration must be minimized if a conservation program is to be effective. In addition to the techniques previ-

ously described, water can be prevented from contacting the structure by covering the surface with a waterproof membrane or coating and by carrying the water away in drains and pipes. More information is available in ACI's *Guide to the Use of Waterproofing, Dampproofing, Protective and Decorative Barrier Systems for Concrete*.

6.1 MEMBRANES AND OVERLAYS

Using membranes or overlays is probably the best means of sealing a large area of concrete that is porous or contains numerous cracks (particularly slab roofs and retaining walls).

The overlay should always be applied to the pressure face if water flows through the concrete. The usual materials are mastic asphalt, tar-impregnated felt, PVC and synthetic rubber sheet. A large number of proprietary overlay products are available. In selecting an overlay system, the following questions should be asked:

- a. should it be rigid, flexible, or extensible?
- b. is it suitable for exposure to a wide or narrow temperature range? (An exposed concrete slab may experience a 50°C temperature range; 300 mm of earth will reduce the temperature range by 15°C.)
- c. is it susceptible or resistant to ultraviolet light?
- d. how long will it last?

The main disadvantage of overlays is that use below grade involves considerable earth removal before placement. One manufacturer advocates coating subterranean walls by injection from above grade, but this technique is far from foolproof. It is advisable to ask to see field-test data and full manufacturer's literature on membranes and to compare tests with the intended use (see Perkins).

6.2 COATINGS

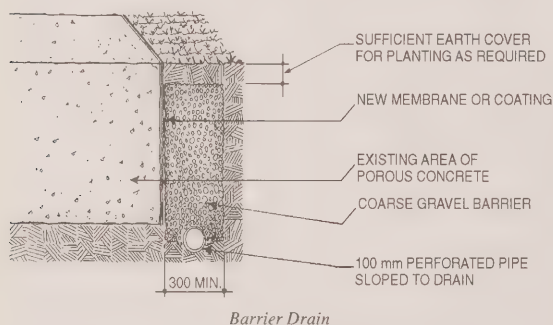
Like overlays, waterproof coatings are used to prevent water entering porous concrete by sealing the surface pores with an impermeable layer of sealant or hydrophobic material. However, there are some limitations on their use. Coatings, with the exception of bitumen, are not normally used to waterproof subterranean work. The waterproof coatings used on concrete – linseed oil, waxes, metallic stearates and epoxies – are generally not recommended for historic concrete structures, because they alter the surface appearance of the concrete.

Silicone water repellants applied in an organic solvent have been used successfully on concrete. Unlike the traditional coatings, they do not seal the surface but line the pores of concrete, thereby altering its surface tension and making it water-repellent rather than absorbent. The silicone barrier inhibits the penetration of low-pressure water, but allows the diffusion of water vapour. Silicones impart no "finish" to the treated surface, but they do have significant disadvantages. Their effectiveness is unpredictable and temporary. There is also evidence that, in some conditions, they contribute to spalling (see Ritchie). Thus, while silicones can improve the moisture shedding properties of sound walls temporarily, they should be applied with care and only on the advice of a historic concrete specialist.

6.3 DRAINS AND BARRIERS

Drainage of a site is not a concrete repair technique, but should be considered an integral part of every concrete conservation program. Whatever the care exercised in the design of drains in historic structures, they often become overgrown and blocked. If cleared out and allowed to function for a season, existing drains might remove enough water to avoid expensive excavation and membrane installation.

Barriers effectively divert water that would otherwise percolate horizontally through the earth to a vertical wall. The simplest barrier consists of a gravel-filled trench with a perforated drain at the bottom to carry excess water away from the wall face.



7.0 CLEANING AND STAIN REMOVAL

Concrete historic structures do not normally require general cleaning; more often special cleaning of exceptional stains is required.

Stains can be removed by mechanical methods including sand and water blasting, grinding, steam cleaning, brushing and scouring. Or they may be removed by chemical methods including the use of specific chemicals according to the nature of the stain.

Caution: Prior to the use of any chemical cleaning methods, Material Safety Data Sheets (MSDS) must be consulted (see bibliography).

The chemical (applied by brush or poultice) will dissolve the stain or bleach it, so that it will not show. Strong acids should be avoided, because they will leave the surface roughened. Most cleaning chemicals are toxic; safety precautions should be observed and contact with the skin and inhalation should be avoided.

For best results, all cleaning should be preceded by tests in inconspicuous locations.

7.1 POULTICING

The poultice technique is quite simple. A smooth paste is made of an appropriate solvent (e.g. toluene, xylene, benzene) and an absorbent, chemically inert, finely ground powder (common ones are talc, fuller's earth, bentonite, powdered silica, diatomaceous earth, hydrated lime [calcium hydroxide] and whiting (calcium carbonate).

The paste is trowelled in a thick layer onto the stained surface. The solvent dissolves the stain which is then absorbed into the poultice as the solvent evaporates. The poultice is removed and a fresh one applied until the stain is lifted out.

7.2 METALLIC STAINS

Deep metallic stains of long standing are virtually impossible to remove from concrete. However, the following methods can be tried:

a. Iron rust:

Light rust stains can be removed by mopping the area with a solution of 1 kg of oxalic acid in 10 L of water and scrubbing with clear water (a small amount of ammonium bifluoride will hasten removal). The use of 10 percent hydrochloric and phosphoric acid is more direct, but will slightly roughen (etch) the surface. Rinse the surface with clean water after treatment.

Deep rust stains may respond to poultices of ammonium citrate or sodium citrate (one part), glycerine (seven parts), and water (six parts) applied as described in 7.1 above.

b. Copper and bronze:

Apply an ammonium chloride or aluminium chloride poultice, then scrub with water.

7.3 OIL

Deeply soaked-in oils are also difficult to remove completely, as they tend to penetrate concrete surfaces. Probably the most effective method is to remove surface oil by scrubbing with soap, scouring powder and trisodium phosphate or by sponging the stain with carbon tetrachloride. (Use carbon tetrachloride only in well-ventilated conditions or with an appropriate filter mask.) Alternatively, apply poultices of benzene or five percent sodium hydroxide, as described in 7.1 above.

7.4 BITUMEN AND ASPHALT

Bitumen stains are among the most difficult to remove from porous surfaces. Surface stains can be removed by scrubbing with warm kerosene, then carbon tetrachloride or trichloroethylene. Deep stains will never be completely removed, but poultices with appropriate solvents are effective (see 7.1 above).

Surface deposits of asphalt can be removed by cooling with ice, then chipping or scraping away the embrittled material.

7.5 PAINT

Freshly spilled paint should be soaked up (not wiped) with absorbent material, then scrubbed with scouring powder and water. Wait three days for paint to harden.

Dried paint can be removed by softening with an alkali paint stripper, then scraping and scouring. Organic solvents should not be used as strippers, as they act as vehicles for carrying the pigment deeper into the pores of the concrete. Penetrated colour can be removed by a diluted hydrochloric or phosphoric acid wash.

Organic solvent poultices are also useful as paint removers. One such poultice consists of methyl acetate (10 parts), benzene (25 parts), denatured alcohol (18 parts) and ethylene dichloride (8 parts). The poultice should be followed by a hydrogen peroxide bleach.

Aerosol paint and felt-tip pen can be removed with commercial products (see 8.0 below for suppliers).

If all other methods fail, a low-pressure air abrasive will remove the colour at some sacrifice of surface finish.

7.6 ALGAE, LICHENS, MOSSES AND MILDEW

Scrubbing with a weak solution of bleach or five percent formalin in water will remove algae, lichens and mosses from concrete. Resistant growths may require soaking with a solution of sodium orthophenylphenate (about 25 g/L of water) for about one hour. It should then be hosed off and followed by a four percent solution of dichlorophen washed over the surface to leave a toxic residue which will prevent their regrowth for some time.

The recommended solution for treating mildew is 25 g laundry detergent, 70 g trisodium phosphate, and one L bleach, dissolved in three L water.

7.7 GENERAL CLEANING

Standard masonry cleaning practices, particularly those suitable for limestone, can be used for cleaning historic concrete structures. Those based on acids should be avoided. There are three basic approaches:

a. Water sprays:

The traditional method of cleaning heavy accumulations of atmospheric dirt from concrete is by softening the deposits with water sprays and wooden scrapers and bristle brushes. Excessive quantities of water, however, can harm the structures by saturating surfaces, metal fittings and reinforcements normally beyond the reach of rain. Such treatment should therefore be done in the late spring or summer to avoid damage from freezing.

b. Alkaline cleaners:

Chemical cleaners are based on caustic soda and are used primarily for cleaning moderately soiled concrete. The chemical must be removed by water washing or surface efflorescence will result.

c. Abrasives:

Sandblasting will achieve immediate dramatic results without the dangers of water penetration. However, irreparable harm can be done to a historic surface if blasting is too severe. Low

nozzle pressures, smooth fine grits, diligent supervision and experimentation on test patches are essential. Water blasting will remove surface accumulations of mosses, lichens, dirt or paint.

Whenever air abrasive methods are contemplated, test the pressures to be used to reduce the risks of irreparable damage to concrete surfaces. If properly used, air abrasives can be effectively employed for removing accumulated paint finishes.

8.0 ASSOCIATIONS AND SUPPLIERS

8.1 ASSOCIATIONS

Canadian Testing Association
3420 St. Joseph Blvd. E.
Montréal, PQ.
H1X 1W6

Association of consulting firms certified by CSA for the testing and analysis of concrete. Laboratories are certified according to the tests they are equipped and qualified to carry out.

Canadian Portland Cement Association (CPCA)
116 Albert Street
Ottawa, ON
K1P 5G3

CPCA
Ontario Region
Suite 1402
365 Bloor Street
Toronto, ON
M4W 3L4

8.2 SUPPLIERS

Adhesives Engineering Company
1411 Industrial Road
San Carlos, CA
94070

Manufacturer of epoxy repair systems for concrete structures. Contact the head office for names and addresses of Canadian licensees.

Construction Product Distribution Services
P.O. Box 364
Concord, ON
L4K 1C5

National Boring & Sounding Co.
1130 Sherbrooke Street
Montréal, PQ
H3A 3K4

Pro So Co Inc.
P.O. Box 1578
Kansas City, KS
66117

Distributor and manufacturers of masonry water repellants and consolidants based on ethyl-silicates and silanes.

Serv-pro Distributors
168 Higgins Avenue
Winnipeg, MB
R3B 0B8

Distributor for *Graffiti Gobbler*: ink, paint, chewing gum remover.

Sica Chemical of Canada
601 Delmar Avenue
Pointe Claire, PQ
H9R 4A9

Manufacturer of epoxy repair materials:

Thoro System Products of Canada
58 Hymus Road
Scarborough, ON
M1L 2C7

Manufacturer of concrete patching and coating materials.

9.0 BIBLIOGRAPHY

- American Concrete Institute.** 1979. *Guide to the Use of Waterproofing, Dampproofing, Protective and Decorative Barrier Systems for Concrete*. ACI 515, IR-79. Detroit.
- Ashurst, J., and F. Dimes.** 1977. *Stone in Building: Its Uses and Potential Today*. Architectural Press, London.
- Champion, S.** 1961. *Failure and Repair of Concrete Structures*. Contractor's Record, London.
- Feldman, R.F.** 1977. *Non-destructive Testing of Concrete*. Canadian Building Digest No. 187. National Research Council, Ottawa.
- Johnson, S.M.** 1965. *Deterioration, Maintenance and Repair of Structures*. McGraw-Hill, New York.
- Labour Canada.** 1991. *Workplace Hazardous Materials Information System (WHMIS)*. Sub-section: *Material Safety Data Sheets (MSDS)*. Labour Canada and Consumer and Corporate Affairs offices in major Canadian cities. Also the Canadian Centre for Occupational Health and Safety, Hamilton.
- Lea, F.M.** 1970. *Chemistry of Cement and Concrete*. E. Arnold, London.
- _____. 1981. *Grouting Methods and Materials for Soil and Rock Foundations and Massive Masonry*.
- _____. 1981. *Surface Repairs to Concrete Marine Structures*.
- Parks Canada.** 1994. "Concrete Deterioration and Defects," *Architectural Conservation Technology*. VI.1.2. Ottawa.
- Perkins, P.H.** 1977. *Concrete Structures: Repair, Waterproofing, and Protection*. John Wiley & Sons, New York.
- Portland Cement Association.** 1982. *Concrete Information: Removing Stains and Cleaning Concrete Surfaces*. Skokie, IL.
- Ramachandran, V.S., and J.J. Beaudoin.** 1979. *Removal of Stains from Concrete Surfaces*. Canadian Building Digest No. 153. National Research Council, Ottawa.
- Ritchie, T.** 1974. *Silicone Water-Repellents for Masonry*. Canadian Building Digest No. 162. National Research Council, Ottawa.
- Stafford, B.F.** 1967. *Poultice Method for Treating Bituminous Stains on Masonry Products*. Building Research Notes No. 60. National Research Council, Ottawa.
- Torraca, G.** 1976. *Brick, Adobe, Stone and Architectural Ceramics: Deterioration Processes and Conservation Practices*. Preservation and Conservation: Principles and Practices. Preservation Press, Washington, DC.

Illustrations are the property of the Heritage Conservation Program, unless otherwise noted.

VOLUME VI

CONSERVATION OF MATERIALS

2.1

MASONRY

STRUCTURE AND PROPERTIES

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: G. ATTAR

CONTENTS

1.0 INTRODUCTION

2.0 STONE

2.1 TYPES OF ROCK (STONE)

2.1.1 Igneous

2.1.2 Sedimentary

2.1.3 Metamorphic

2.2 PROPERTIES OF STONE

3.0 BRICKS

3.1 TYPES OF CLAY BRICKS

3.2 PROPERTIES OF BRICKS

4.0 BIBLIOGRAPHY

1.0 INTRODUCTION

This article is intended to familiarize personnel involved in conservation with the structure and properties of masonry, and to serve as an aide-mémoire for architects and engineers at the design or managerial levels.

The term “masonry” is usually applied to a construction built up of unit materials such as stone, clay or concrete, set in mortar or laid without it (dry walls), and possibly reinforced to increase its tensile and shearing strength. Newer prefabricated masonry panels often consist of thin slabs of reinforced masonry, attached to steel or reinforced-concrete frames by metal anchors.



Several Types of Brick Deterioration

Masonry is one of the oldest building methods in the world. Earth, stone and clay were often the only suitable materials,

other than wood, that were at hand. Historically, masonry served both an environmental and a structural purpose: it provided shelter from the elements and supported upper floors and roof structures.

This article identifies the principal types of stone, bricks and mortars used in period masonry construction and briefly describes their composition, characteristics, properties and uses.

2.0 STONE

Stone is rock that is cut, shaped, broken, crushed or otherwise physically modified for use. It may be obtained from surface excavations (quarries) or from elaborate underground mines using such means as wedges, drills, diamond saws, wire saws and explosives.

Stone is usually composed of minerals such as quartz, feldspar, mica, amphibole, chlorite, calcite, dolomite, serpentine and pyrite. The combination of these minerals determines its physical and chemical properties.

2.1 TYPES OF ROCK (STONE)

Based on their origin, rocks (and stone) are classified as igneous, sedimentary or metamorphic.

2.1.1 *Igneous*

Igneous rocks are sometimes called “unstratified” or “primary” rocks. They are formed by the solidification of a hot, melted material known as magma. Depending on the speed at which the magma cools, these rocks can have coarse- or fine-grained crystals, giving them a distinct texture and appearance.

Granite, the chief building stone in this category, is an aggregation of feldspar and quartz, usually with some hornblende and mica. Its colour – often gray, yellow or red – is derived from the colours of its component parts. Due to its strength and durability, granite is used for foundations, columns, steps, thresholds and watertables.

2.1.2 *Sedimentary*

As implied by their name, sedimentary rocks are formed by the sedimentation, or settling, of particles originating from the disintegration of pre-existing rocks, from chemical reactions or

from the breaking up of shells, corals and the remains of other marine animals. Under great pressure, these particles are cemented by such materials as silica, lime carbonate, iron oxide or clay. The properties of sedimentary rocks therefore, depend largely on their mineral composition and cementing material.

The two principal building stones in this group are limestone and sandstone.

Limestone is composed of calcite (calcium carbonate) or dolomite (calcium-magnesium carbonate) or both. Most limestones are formed from marine shells or reworked shell fragments, although the most popular commercial varieties are very fine-grained chemical precipitates. Depending on the presence of iron oxide and of the impurities, limestone may be white, cream, yellowish-brown or grey.

Sandstone is defined by the American Society for Testing and Materials as “a consolidated sand in which the grains are composed chiefly of quartz and feldspar, of fragmental texture, and with various interstitial cementing materials, including silica, iron oxides, calcite or clay” (*Conservation of Historic Stone Buildings and Monuments*, p. 52). Commercial sandstone is predominantly composed of quartz grains 0.1 to 2 mm in diameter. The numerous remaining voids give this building stone considerable porosity.

2.1.3 Metamorphic

Metamorphic rocks are igneous or sedimentary rock masses in which new minerals, textures or structures are formed by the combined action of heat and pressure. Metamorphic rock falls into two groups: cataclastic rocks formed by purely mechanical forces, such as shearing and crushing; and recrystallized rocks formed under the influence of metamorphic pressure and temperatures. Marble and slate belong to the latter group.

Marble, widely used as a building stone because of its beauty, is a crystallized limestone which can be white (pure marble), gray, red, blue, green or black depending on the presence of oxides of iron, silica, mica, graphite, serpentine and carbonaceous matter.

Slate is a silicious clay rock formed from clayey shales by metamorphic action. It may be red, green, black, grey or purple. Good quality slate is strong and durable. Two of its characteristics are that its structure shows distinct cleavages suitable for splitting and that it is relatively impervious to

moisture perpendicular to these cleavages. Some slates may be split into thin sheets for roofing or cut into thick slabs for use as damp-proof courses, counter tops and floor tiles.

2.2 PROPERTIES OF STONE

In general, the quality of a stone is based on its appearance, strength and durability. These characteristics depend on such chemical, physical and mechanical properties as composition, colour, texture, density, porosity, hardness, water absorption and adsorption, compressive and tensile strength, modulus of elasticity, modulus of rupture and thermal properties.

The colours and textures of stones are influenced by the colour of the predominant mineral and by grain size. Some may also change colour because of unstable pigments.

The strength of a stone is very important, especially when it is to be used in foundations, piers or other structural bearing elements. Strength is usually expressed by compressive strength, which is determined by the load required for the failure of a specimen divided by the bearing surface of that specimen. The tensile strength of stones is important for resistance to bending stresses when stones are used as bending members, such as lintels, and for resistance to stresses resulting from expanding salts and freezing water.

Porosity and water absorption and adsorption are the properties that determine the ease with which the water can infiltrate and circulate inside the stone. They are very important where frost and wet weather occur. A porous stone is seriously affected when it contains a great deal of water, since frost is the most active agent in the destruction of stone. Water also affects the stone chemically by dissolving its salt and soluble components and by activating chemical reactions.

The modulus of elasticity, the modulus of rupture and the thermal expansion of a stone also determine its behaviour under stress and thermal change. See Winkler for more information.

3.0 BRICKS

Bricks are building materials usually made from clay, shale or other materials moulded as rectangular blocks and baked or burned in a kiln. Unfired bricks, which are less common in period structures in Canada, include adobe bricks (moulded

from earth or clay mixed with straw and hardened by the sun) and concrete or cement and sand-lime bricks (which are cured).

Clay, the chief component of bricks, is a natural, earthy, fine-grained material which develops plasticity when mixed with a limited amount of water. It is constituted largely of sand and alumina and may contain various quantities of iron, chalk and manganese dioxide.

Shale is a fine-grained laminated sedimentary rock made up of silt and clay-sized particles. It consists of quartz, clay minerals, other minerals, such as carbonates, iron oxides, feldspars and organic matter.

3.1 TYPES OF CLAY BRICKS

In general, clays (and consequently bricks) are classified as calcareous (containing calcium carbonate which imparts a yellowish colour) or noncalcareous (containing feldspar grains and iron oxide which impart a red or salmon colour).

On the basis of the method of manufacture, bricks can also be classified as handmade bricks, wire-cut bricks or pressed bricks.

Handmade bricks, because of the high labour costs involved in moulding, are expensive today. They are generally made to meet specific requirements. Wire-cut bricks are produced by forcing the plastic clay through a mouthpiece or die to form a continuous rectangular ribbon with a cross section equal to the flat or end side of an unburnt brick. The ribbon is then cut into brick-sized pieces by a series of tightly stretched wires. Pressed bricks are machine moulded. They are sound and of regular shape and size.

Based on use, bricks can also be classified as common – ordinary bricks used where appearance is not important (for example, walls, piers, foundations and backing for stone or terra cotta). Facing bricks are made or selected for their colour, shape or texture. They are used in exposed surfaces of walls for their attractive appearance and weathering resistance. Common bricks may back them.

Other special types of bricks are glazed, fire, engineering, sand-lime and hollow.



Masonry Arch and Wall

3.2 PROPERTIES OF BRICKS

The properties of bricks depend on their earth or clay composition, method of manufacture and degree of burning. Since the composition of brick earths varies according to locality and position in a claypit, and the method of manufacture varies from one place to another, bricks have many colours, textures and chemical and mechanical properties.

Bricks may be red, orange, yellow, white, grey, purple, blue, brown and black or intermediate shades of these depending on their composition. Ferric oxide (iron) in the clay imparts the characteristic red colour; manganese and manganese oxides, a brownish or blackish colour. Lime will produce yellow or even white bricks if it is present in sufficient proportion and the iron content is very low.

Other components determine the nature of the brick. For example, silica in the right proportion produces hard, rigid bricks, but in excess makes them brittle and lacking in cohesion. The correct amount of alumina makes clay plastic, thus facilitating moulding and providing a flux during burning; too much, however, will cause the bricks to warp, crack and shrink excessively. Lime or chalk, which reduces shrinkage, should be present in very fine particles, as otherwise it will slake and expand if the bricks absorb moisture.

In general, handmade bricks have richer textures, while machine-made bricks have smooth faces. Certain dense,

smooth-faced bricks may, however, be difficult to lay owing to their lack of “suction” which prevents ready adhesion of the mortar. This lack of adhesion causes narrow fissures between the bricks where water may penetrate.

The degree of burning is important. Correctly burned bricks are hard, overburned bricks are badly warped and discoloured, and underburned ones are very soft. Porous, underburnt bricks are particularly vulnerable to damage by frost action. Cracking may result from quick drying and cooling of the bricks in the kiln.

Permeability, porosity and absorption are important properties of bricks since they affect strength and durability.

The permeability of a brick depends largely on its pores. A closed-pored brick freely absorbs water, which does not readily evaporate; a more open-pored brick absorbs less moisture which evaporates more easily because of the increased air circulation. If the pores are continuous from face to face, they may allow rainwater to pass through them to the inside of the masonry element, causing efflorescence or salting. Bricks should be somewhat porous (the pores being neither too fine nor too open) to permit strong adhesion of the mortar.

Bricks which are very absorbent when dry are usually soaked before laying to prevent them from reducing the strength and adhesion of the mortar by extracting too much water from it. A low absorption rate causes sliding on the mortar bed, particularly with cement mortars.

In general, good bricks are hard, well-burnt and free of cracks, chips and large particles of lime. They ring clearly when struck with a trowel.

4.0 BIBLIOGRAPHY

- Burnell, G.R.** 1910. *Rudimentary Treatise on Limes, Cements, Mortars, Concretes, Mastics, Plastering, Etc.* 6th edition. Crosby Lockwood and Son, London.
- Conservation of Historic Stone Buildings and Monuments, Committee on.** N.S. Baer, Chair. 1982. *Conservation of Historic Stone Buildings and Monuments*. National Academy Press, Washington, DC.
- D'Amours, G.** 1984. *Masonry Bibliography and Reference*. EA-PC-84-04.
- Graham, F.D., and T.J. Emery.** 1945. *Audels Masons and Builders Guide #4*. Theo. Audel and Co., New York.
- Harris, C.M.** ed. 1975. *Dictionary of Architecture and Construction*. McGraw-Hill Book Company, New York.
- Huntington, W.C., and R.E. Mickadeit.** 1975. *Building Construction, Materials and Types of Construction*. 4th edition. John Wiley and Sons, New York.
- Kelsey, W.E.** 1974. *Building Construction*. David and Charles, Newton Abbott, UK.
- Lowndes, W.S.** n.d. *Building Stone Foundations - Masonry*. International Textbook Company, Scranton, PA.
- Mackay, W.B.** 1970. *Building Construction*. 5th edition. Vols. 1 and 2. Longman Group Ltd.
- McKee, H.J.** 1973. *Introduction to Early American Masonry*. National Trust for Historic Preservation and Columbia University, Washington, DC.
- Parker, H., C.M. Gay and J.W. Macguire.** 1958. *Materials and Methods of Architectural Construction*. 3rd edition. John Wiley and Sons Inc., New York.
- Winkler, E.M.** 1973. *Stone: Properties, Durability in Man's Environment*. Springer Verlag, New York.

Illustrations are the property of the Heritage Conservation Program, unless otherwise noted.

VOLUME VI

CONSERVATION OF MATERIALS

2.2

MASONRY

DETERIORATION

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: G. SIMISON

CONTENTS

1.0 INTRODUCTION

2.0 DEFINITIONS

3.0 CAUSES OF DEPOSITS, STAINS AND DECAY

4.0 MOISTURE

- 4.1 MOISTURE PENETRATION AND
MOVEMENT IN POROUS MATERIAL
 - 4.1.1 *Absorption*
 - 4.1.2 *Capillary Action*
 - 4.1.3 *Osmotic Pressure*
 - 4.1.4 *Atmospheric Vapour Penetration*
-

5.0 ADSORPTION

6.0 SOLUBLE SALTS

- 6.1 CRYSTALLIZATION (FLORESCENCE)
 - 6.2 EFFLORESCENCE
 - 6.3 SUBFLORESCENCE
-

7.0 ATMOSPHERIC POLLUTION

- 7.1 GASEOUS AND VAPOUR POLLUTION
 - 7.2 PARTICULATE POLLUTION
 - 7.2.1 *Natural Dust*
 - 7.2.2 *Soot*
 - 7.3 AEROSOLS
-

8.0 BIOLOGICAL AGENTS

- 8.1 TREES AND PLANTS
 - 8.2 ALGAE AND LICHENS
 - 8.3 FUNGI AND MICRO-ORGANISMS
 - 8.4 ANIMALS AND BIRDS
 - 8.4.1 *Boring Animals*
 - 8.4.2 *Birds*
-

9.0 RUST AND CORROSION

- 9.1 NATURAL RUST ON STONE
 - 9.2 CORROSION OF METAL ELEMENTS
-

10.0 PATINA

11.0 APPLIED COATINGS

12.0 ORIENTATION AND LOCATION OF MASONRY SURFACES

- 12.1 ORIENTATION
 - 12.1.1 *Wind*
 - 12.1.2 *Thermal Stress*
 - 12.2 LOCATION
-

13.0 SPECIALISTS AND CONSULTING SERVICES

- 13.1 SCIENTIFIC RESEARCH ORGANIZATIONS
-

14.0 BIBLIOGRAPHY

1.0 INTRODUCTION

The preservation of historic masonry involves a continuing fight against interrelated forms of deterioration. This article describes the causes, appearance and chemical structure of deposits, stains and decay, and their effect on masonry surfaces.

Deposits and stains are important aspects of masonry degradation and not just aesthetic problems that can be cured by cosmetic treatment. They can have effects beyond the surface layers of masonry and may indicate structural defects or other internal problems. The conservator must understand the characteristics and behaviour of the elements that cause masonry surface deposits and stains before planning cleaning, repair and preventive treatment.

This article is closely related to Vol. IV.4.1 "Masonry Structures: Cleaning."

2.0 DEFINITIONS

Amorphous: noncrystalline.

Anion: the ion in an electrolyzed solution that migrates to the anode; a negatively charged ion.

Calcicolous: that which flourishes on soils or rocks rich in calcium carbonate.

Calcite: a crystalline form of calcium carbonate showing trigonal symmetry and a great variety of mineral habits. It is one of the most common minerals in association with igneous and sedimentary rock.

Capillarity: the elevation of liquid in a capillary tube or tubes.

Cation: the ion on an electrolyzed solution that migrates to the cathode; a positively charged ion.

Colloidal: the state of subdivision of matter in which the particle size varies from that of true 'molecular' solutions to that of coarse suspensions. The particles are electrified and have a large amount of surface activity.

Hydrolysis: decomposition of a compound by reaction with water, the water also being decomposed.

Microporosity: the ability of a material to absorb moisture.

pH value: a measure of a solution's acidity. A pH below seven indicates acidity; one above seven, alkalinity.

Refractory: treated substance resistant to heat, corrosion and so on.

Rhizome: an underground stem consisting of more than one year's growth, usually lying horizontally in the soil. Resembles a root, but bears scale leaves and one or more buds.

Silicolous: that which flourishes on soils or rocks rich in silica.

Solution: the complete dissociation of a mineral in a solvent.

Super Saturated: solution containing solvent in excess of equilibrium.

Symbiotic Association: joining of two organisms for mutual association advantage.

Thallus: a plant body in which the root and shoot are not differentiated. It may be a single cell, a filament of cells or a complicated multicellular structure.

3.0 CAUSES OF DEPOSITS, STAINS AND DECAY

The most significant causes of deposits, stains and decay are ground moisture and salts, atmospheric pollution, biological agents and corroding metallic elements. All these depend on the presence of moisture and some are interdependent. Some artificial coatings cause deposits and stains that are not necessarily destructive, but are unsatisfactory in appearance. Deposits that are destructive to the masonry surface should be removed and their causes eliminated.

Patina, which is often a beneficial stain, is caused by various deposits on, or in, the historic masonry. It is usually harmless and adds a pleasant, rich colour to the masonry surface and need not be removed.

The following table lists various environmental agents which bring about the deterioration or degradation of materials:

Major Environmental Agents of Deterioration

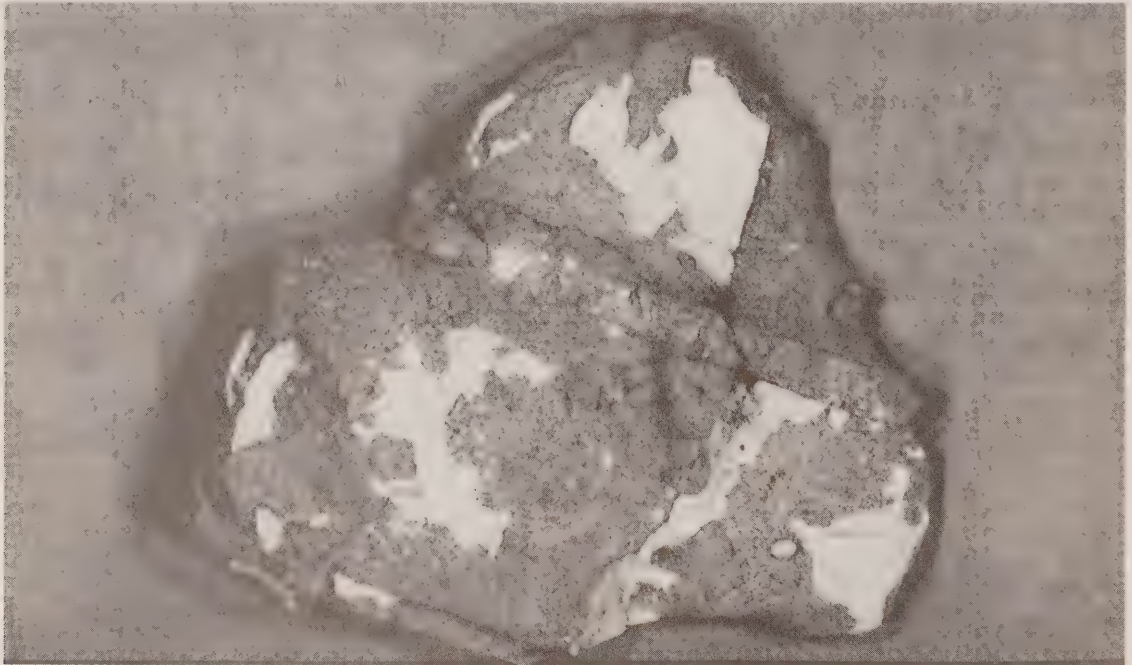
Chemical	Physical	Biological
Oxygen	Radiant energy	Vegetation
Ozone	Heat (high)	Insects
Carbon dioxide	Cold (frost)	Animals
Sulphur dioxide	Abrasives	Humans
Hydrogen sulphide	Water	
Acids, alkalies, salts	Matter in motion	
Water		
Organic solvents		

Source: Based on a table by S. Keck (see Timmons 1976).

Note: There can be interactions involving the various agents. Photochemical and electrochemical actions result from the interaction of physical and chemical agents. Biological agents use physical-chemical means to ingest and digest matter.

4.0 MOISTURE

Moisture is the major element in the process of masonry surface deterioration. It is a catalyst that encourages deterioration by soluble salts, atmospheric pollution, biological agents, rust, corrosion, patina and applied coatings. For this reason, it is essential to understand how moisture enters and is held in the internal structure of masonry materials.



5 2 3 4 5 6 7 8 9
 26 27 28 29 30 31 32 33

Spalled Section of Brick Wall Due to Frost Damage

All masonry material is porous and hence, permeable by water and water vapour to varying degrees, depending on its capillary structure. This capillary structure provides a very large internal surface that can attract fluids by absorption and solids by adsorption (see 4.1 and 5.0 below).

A sharp fall in temperature will cause water in the pores of the masonry material to freeze and subsequently increase in volume by 10 percent. This action results in mechanical stress that can break the pore walls and ultimately remove entire surface layers of masonry material, leaving masonry surfaces with patches of a different colour and texture, lacking the patina and finish of the original wall surface. Moisture penetration and frost damage in masonry are related to pore structure and relative microporosity.

4.1 MOISTURE PENETRATION AND MOVEMENT IN POROUS MATERIAL

Capillary action, osmotic pressure and atmospheric vapour penetration are the main forces affecting the migration of moisture in masonry.

4.1.1 *Absorption*

Masonry absorbs moisture from the ground, the air and adjacent building elements. It travels in masonry upwards (rising damp), downwards (falling damp) and horizontally (horizontal movement of damp).

Water pooling near the bottom of the structure because of ineffective drainage can cause rising damp. Rainwater that hits the masonry surface can cause falling damp and horizontal movement of damp through the pores.

Introduced moisture often brings with it salts and other soluble substances in solution.

4.1.2 *Capillary Action*

Capillary action of the porous material causes suction that draws water, often with salts in solution, up from the ground. This action depends on the environment of the masonry and on the shape and size of the masonry's pores; the smaller the pores, the higher the rise of water. Masonry of high microporosity (with pores about five microns in size) experiences greater capillary pressure. Its ability to attract and hold more water can result in faster deterioration.

4.1.3 *Osmotic Pressure*

Osmotic pressure is created by salt solutions of different concentrations carried up into the masonry by capillary action. Osmotic pressure can affect the extent and direction of water travel. It attracts water to provide equilibrium with the concentrated salt solutions. Unlike capillary action, which has a theoretical migration limit, osmotic action can rise to moisture higher and higher. In old masonry, this rising moisture can reach up to 10 m above ground level.

4.1.4 *Atmospheric Vapour Penetration*

Atmospheric water vapour, which is always present to varying degrees in the air, condenses on the masonry surface and penetrates into the pores where a specific quantity is held at equilibrium with the relative humidity of the air. Condensation occurs when there is a decrease in masonry surface temperature or an increase in water vapour level.

5.0 ADSORPTION

Adsorption is the adhesion of molecules of gases, or of ions or molecules in solutions, to the surfaces of solid bodies with which they are in contact (Winkler, p. 29). A porous material is much more reactive than a compact one, because of the large internal surface area.

6.0 SOLUBLE SALTS

Rock matrices, cement and mortar materials contain many minerals which are soluble to varying degrees in water and weak acids. Typical examples of such minerals are: calcium and magnesium carbonate, silicates, calcium, magnesium and sodium sulphate and various clay minerals. Potassium sulphate and sodium chloride are also soluble, but to a lesser degree.

Silica cements, found mainly in igneous rocks and in siliceous sandstones, are impervious to most natural solvents.

In addition to their presence in building materials, or their generation from the decomposition of such material, soluble salts are found in the soil (nitrates of sodium, potassium and calcium), in the air (sodium chloride in sea air) and in the excreta of animals, birds and bats. The use of de-icing salts in cold climates provides an additional source. The use of some

types of cleaning agents on stone can also result in the deposition of soluble salts in stone.

Salts may act directly on the surface of the masonry or they may be drawn into the pore structure by capillary action. The crystallization of salts in the masonry can cause its deterioration.

6.1 CRYSTALLIZATION (FLORESCENCE)

Crystallization occurs in solutions between the state of saturation and supersaturation. With the loss of solvent, crystals expand and may break the walls of the pores in the masonry by exerting internal mechanical pressure.

6.2 EFFLORESCENCE



Efflorescence and Mortar Deterioration

Efflorescence is the crystallization of soluble salts at the end of the pores as the moisture evaporates at the masonry surface. Usually appearing as blotches, patches and margins of white salt crystals, efflorescence indicates the limits of salt migration and the level of rising damp in the masonry. It is clearly visible on brick walls where it contrasts against the red brick. As a result of kilning, bricks often contain large amounts of sulphate which increase the incidence of efflorescence.

6.3 SUBFLORESCENCE

Subflorescence, which has the same appearance as efflorescence, is the crystallization of the salts just beneath the stone surface. Subflorescence may cause the surface layer of the masonry to exfoliate or spall.

7.0 ATMOSPHERIC POLLUTION

Masonry buildings are exposed to natural atmospheric agents, and also to the action of deleterious human-made pollutants.

Air pollution consists of particles, aerosols and gases. Pollution of the atmosphere by acid gases is the main cause of decay of masonry material containing calcium carbonate and calcite, such as limestone, marble and calcareous sandstone. Solid products of combustion, such as soot, carry acidic materials which disfigure masonry surfaces. Aerosols, tiny drops of liquid or very small particles suspended in the air, are also acidic.

The average amount of solid and gaseous atmospheric impurities which cause decay is higher in densely populated areas than in rural districts and varies considerably from one region of the country to another.

Water vapour, which is often overlooked as a cause of deterioration, represents a major problem. It condenses on masonry and attracts polluting elements. It also carries aerosols which are very harmful to masonry surfaces (see 7.3 below).

Wind accelerates all forms of masonry surface deterioration caused by atmospheric pollution. The combined action of pollutants can darken the masonry surface and cause blistering and scaling. This crust may eventually be removed by cleaning or it may exfoliate, exposing deeper layers and subjecting them to similar attack.

The complicated series of reactions to atmospheric pollution is exemplified by the two-phase deterioration of carbonate rocks:

1. Superficial attack: the carbonate rock is gradually transformed from the outside inwards, forming a hard, impermeable crust of gypsum mixed with soot and dust. On stones that are not very porous, this crust may adhere well and may actually be protective to some extent, as it is resistant to fumes.
2. The second phase is characterized by the break-up of the crust, often caused by the percolation of saline solutions into the interior of the stone. The surface becomes powdery and the crust is deformed and eventually detached, exposing a sensitive interior easily eroded by rain.... The cracks and crevasses are probably intensified by the fact that the linear dilation of gypsum is about five times that of calcite. The crystals slide over each other, gypsum recrystallizes in the fissures, and cornices and carvings may be seriously damaged (Sneyers and DeHanau 1968).

7.1 GASEOUS AND VAPOUR POLLUTION

The atmosphere is composed of about 78 percent nitrogen, 21 percent oxygen and one percent carbon dioxide, argon and other gases.

Gases are all normal constituents of the atmosphere; however, their concentrations can vary considerably. The pollutants that attack stone to the greatest extent are CO_2 , SO_2 , and SO_3 . Listed below are all sources of atmospheric pollution.

- a. Sulphates (SO_2 , SO_3) are produced from the combustion of coal, oil and natural gas which releases sulphur as SO_2 into the atmosphere. Winter heating raises sulphate output to high levels. Other sources of SO_2 are ocean spray and dust from desert flats.

A considerable amount of sulphur dioxide (SO_2) is oxidized by sunlight or by pollutants to form sulphur trioxide (SO_3). This occurs much faster in the presence of a catalytic oxidant such as carbon monoxide (CO) and a high relative humidity in the atmosphere. Sulphur trioxide dissolves in moisture, forming sulphuric acid which increases the acidity of rainwater and water vapour. Sulphuric acid attacks carbonate rocks by converting the carbonates to either calcium

sulphite or calcium sulphate (gypsum). Because gypsum is much more water soluble than calcite, layers of stone surface can be washed away. This consequently increases the rate of deterioration.

- b. Carbon dioxide (CO_2), a minor natural constituent of the atmosphere, has increased since the advent of global industrialization. (Automotive exhaust is credited with more than 60 percent of all industrial exhaust). When in solution CO_2 forms carbonic acid which dissolves calcium carbonate, and hence can erode calcium carbonate stone.
- c. Carbon monoxide (CO) is produced as a result of incomplete combustion. It is not corrosive to stone and it does not oxidize to CO_2 ; however, it acts as a catalyst in the oxidation of sulphates, as mentioned previously.
- d. Chloride is an important constituent of the atmosphere. Some chlorides may convert to hydrochloric acid which readily dissolves carbonate rocks.
- e. Nitrates, usually as NO_2 , convert to corrosive nitric acid in photochemical smog.

The above-mentioned effects of sulphate and carbonate formations can lead to a dark stalactite-like formation beneath horizontal surfaces exposed to rain. Rainwater permeates the stone and eventually gravity causes drops to pass through to the underside of the horizontal surfaces, depositing particles of calcium carbonate or calcium sulphate. These particles accumulate as in the formation of stalactites.

Atmospheric vapour derived from rain or condensation is naturally slightly acidic because it contains dissolved carbon dioxide. Therefore, any atmosphere will affect masonry. The chemical reaction increases with rises in temperature. Pure rainwater can, therefore, cause considerable deterioration in hot, damp climates.

When water vapour containing free sulphuric acid condenses on masonry, the masonry is attacked by the acid. Water vapour may also contain suspended particles of carbon, iron oxide or calcium sulphates (gypsum) which will be deposited on the masonry surface. Condensation is the most common cause of deterioration in low-porosity and compact materials. Rainwater does not cause as much deterioration as condensation because rainwater washes away surface pollutants.

7.2 PARTICULATE POLLUTION

Particulate pollutants are common in industrialized areas. Airborne particles are deposited on masonry surfaces (see 7.3 below). Depending on the nature of the masonry material, the moist particles react as either alkalines or acids and a chemical attack may result. The particles may penetrate into the pores and permanently blacken the building exterior. This is especially common with bricks which have been fired at a temperature of about 900°C. These bricks have submicroscopic capillary systems which keep the surface damp and attract dust. Refractory bricks lack the moisture needed to attract dust and, therefore, retain their original colour for a long time.

7.2.1 *Natural Dust*

Natural dust is particulate matter ranging from approximately one to 100 microns in size. It is primarily composed of terrestrial wind-borne debris, some volcanic dust, and minute amounts of extraterrestrial cosmic dust.

It is often in the form of windblown particles lifted from dry river beds, flood plains, beaches, ploughed fields or construction sites.

The calcite component of dust reacts with acids in rainwater and is converted to gypsum (see 7.0 above).

7.2.2 *Soot*

Tarry matter present in soot causes it to adhere to any material with which it comes into contact. Soot deposits cause extensive disfiguration of buildings. Thick black incrustations, consisting of soot and products of the stone's chemical disintegration, accumulate under projecting features. Soot fills the surface pores of many sandstones causing them to become uniformly darkened. The dissolving action of acid rainfall on limestone washes the exposed surfaces of limestone free of soot, leaving only the protected surfaces affected by crust formation.

7.3 AEROSOLS

Aerosols are tiny drops of liquid particles of matter suspended in the air. The liquid may consist of sulphuric, nitric or hydrochloric acid, while the particles may be sodium chloride from sea-salt or de-icing salts. They range in size from molecules to raindrops. Aerosols can be carried for some distance in the air. When they settle on the surface of masonry, they contribute to its deterioration.

Aerosols are numerous in seaside areas where ingredients such as sulphates and chlorides are derived from natural sources such as oceans and salt flats. Sea spray contains sodium chloride crystals, around which liquid droplets form.

Aerosols are attracted to cold surfaces and produce effects similar to those of condensation even if the surface temperature does not drop below the dew point of the air. The chemical attack on stone is largely caused by the solvent action of water and its dissolved impurities (see 7.1 above).

8.0 BIOLOGICAL AGENTS

8.1 TREES AND PLANTS

Trees and plants growing on or close to a building or monument may directly cause destruction of masonry or may promote deterioration by hindering evaporation of moisture from the walls. Plant growth on monuments indicates poor maintenance, and often results from, as well as causes, deterioration. Vegetation growth generally indicates an abnormally high local moisture content in the building materials and a potential for serious decay.

Plant roots will not usually penetrate sound, uncracked stone or mortar joints. They grow along stone surfaces where they react chemically with the minerals (Winkler, p. 160). Root growth and the slightly acidic sap of the root cells may have an etching effect on marble and limestone. Rotting roots produce humic substances that can stain calcareous stones.

Grasses and the roots of small trees may enter crevices and weak mortar joints of older buildings and cause damage. The acidic secretions of the plants interact with the mineral constituents of the masonry.

Axial pressures on the root tips are high at first but, as the axial growth becomes inhibited, radial pressure increases through the total surface of the root. This causes a wedging force which widens the cracks and joints and offers easier access for moisture.

8.2 ALGAE AND LICHENS

Algae are green, red or brown filaments which thrive on all types of building surfaces, even in industrially polluted environments. In high moisture conditions algae can become slimy,



Roots of plants, mosses and other organic growth protruding into cracked mortar joints, will contribute to the mortar deterioration process.

slippery and, therefore, may be a safety hazard on pavement or stairs. The presence of algae usually indicates a high moisture content in the substratum also and is frequently encountered near rain pipes or in the lower parts of buildings wetted by capillarity. Algae-covered walls are often continuously above the critical moisture content level.

Lichens are formed by the symbiotic association of algae and fungi. There are several types of lichens, but those which cause the greatest disfiguration are the calcicolous varieties which grow on calcareous stone and contribute to their chemical deterioration. Calcicolous lichens grow within the aggregates of minerals, with the greater part of the thallus below the stone's surface. Silicolous lichens grow primarily on igneous rocks on their mineral surfaces. (Winkler, p. 156).

Lichens grow extremely slowly by the addition of concentric rings. The individual rings usually progress at the rate of 1.0 mm in diameter annually. They can tolerate extremes of temperature and survive for lengthy periods without moisture.

Lichens and algae attack stone surfaces through the retention of water, ion exchange and acid secretion. Although there is no

direct evidence that these organisms contribute seriously to the decay of stone, they definitely change the surface texture and should not be tolerated on finely carved, valuable masonry.

Lichens rarely attack buildings and monuments in urban and industrial areas, where there is sulphur and excessive carbon dioxide in the atmosphere. Of all the biological growths on stonework, lichens are the most difficult to eradicate without using substances which may be detrimental to the stone.

8.3 FUNGI AND MICRO-ORGANISMS

Fungi can damage porous building materials. The decay process caused by fungi is not clearly understood; however, fungi indicate high humidity in the material. They also produce carbonic, nitric, sulphuric and some weaker acids which attack silicate minerals. Fungi appear early in the weathering process and often bring about the growth of other organisms.

Moulds, which are a form of fungi, appear as spots or patches and may spread to form a grey-green, black or brown furry layer on the stone surface. Moulds, which feed on organic material, rarely appear alone.

Bacteria cause flaking, powdering and spalling. When present in large colonies, they may cause discolouration (of any conceivable colour). Silicate rocks bearing bacterial pollutants disintegrate slowly at first, but once decay has started, it progresses very rapidly. For this reason silicate rock affected by bacteria is not recommended for exterior use.

Bacteria may obtain energy from sunlight, chemical oxidation or reduction or from existing organic substances in the soil. Some sulphur bacteria convert sulphur to sulphuric acid, which converts the calcite in sandstone into gypsum (see 7.1 above).

8.4 ANIMALS AND BIRDS

8.4.1 *Boring Animals*

Rock borers, abundant in intertidal marine zones, endanger submerged historical monuments on shorelines. Boring is done either by mechanical abrasion or chemical etching.

Mechanical abrasion is caused by the movement of the animal (for example, a boring mussel turning back and forth around its long axis). Various species are mechanical rock borers in carbonate rock, concrete and soft shale. Some dig at a rate of 12 mm per year with a total depth of about 150 mm.

Chemical etching results from the acid secretion of the animal (for example, the boring clam which digs straight, smooth channels to a depth of 100 mm). Chemical borers act only on carbonate rocks (Winkler, pp. 160-61).

8.4.2 *Birds*

Birds such as sparrows, pigeons and house martins take refuge in recesses or under projections of structures. Bird excrement contains organic acids, such as phosphoric and nitric acids, which etch the stone (Winkler, p. 161). Rainwater is more acidic and is therefore more corrosive to stone when mixed with bird excrement.

Phosphoric and nitric acids react with the carbonates in the stone to form calcium phosphates and nitrates. Sulphur crusts are attributable either to bird excrement or air pollution.

9.0 RUST AND CORROSION

9.1 NATURAL RUST ON STONE

Approximately five percent of the earth's crust is iron. The weathering of iron and of minerals which have iron built into the crystal lattice (for example, ferro-magnesian silicates) releases iron to the immediate surroundings of the mineral grain. The process of oxidation and hydration makes nearly insoluble oxides and hydroxides of iron appear as rusty stains. Iron hydroxides, which are the end product of stable weathering in humid and semi-humid climates, can be crystalline or amorphous (Winkler, pp. 164-67).

Natural oxidation occurs in silicate rocks when they lose their iron. The water-soluble ferrous carbonate dissolves readily in water containing CO₂, especially in polluted areas, into ferri-hydroxide that later transforms to finely crystalline FeO-OH, goethite (Winkler, p. 168).

9.2 CORROSION OF METAL ELEMENTS

Depending on the pH value of the environment, corrosion will take place when iron comes in contact with building materials. The most extensive corrosion usually occurs in acid conditions, although significant corrosion has also been observed in alkaline surroundings, particularly when sodium chloride or magnesium chloride is present.

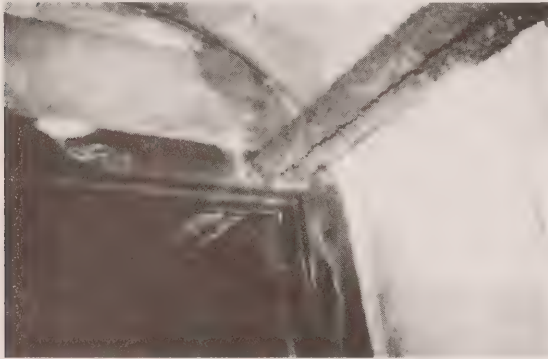
The volume of rust is approximately six to eight times greater than the metal iron used to produce it. This expansion can cause rust burst. Rust burst causes crevices and similar flaws to appear in the material surrounding the iron parts.

Such damage can be avoided by wrapping the iron in lead foil. However, lead itself is attacked when it comes into contact with limestone, mortar or wood. In these circumstances, long-term protection is difficult.

Stone anchors and bolts, as well as rods in reinforced concrete, can cause much damage by rust burst. The same rust burst may be observed during the oxidation of pyrite.

Copper and copper alloys are used for roofing, gutters, downspouts, cornices, decorative details, flashings, hardware and so on. They are fairly resistant to corrosion; however, if unprotected by varnish, they form a film of blue-green copper sulphate that is water soluble. When washed by water, a

green stain forms in the runoff area. This can be prevented with proper drainage. The sulphate remaining on the surface of the copper experiences further reactions, loses its solubility and retards corrosion.



Corrosion of Metal Pipes

10.0 PATINA

Patina is a beneficial form of surface alteration resulting from small chemical and physical changes in the exposed masonry surface. It becomes more dense toward the surface. The alterations may be due to a wide variety of factors which are sometimes, described as “aging” or “weathering.”

There is a point, which is difficult to define, when the alterations to the surface cease to be beneficial and start to cause stresses which lead to physical deterioration of the surface. This can include loss of cohesive and adhesive strength and embrittlement. At this point, the term “patina” is no longer applicable.

For example, the surface alteration in carbonate rock happens by gradual transformation of material from the exterior, inward, forming a hard impermeable crust of gypsum mixed with soot and dust. This crust may adhere well to stones that are not very porous, and may initially be protective, as it resists fumes. Eventually, however, a breakup of the crust occurs. This is caused by the percolation of saline solutions into the interior of the stone followed by subflorescence and spalling of the crust and masonry surface. At this stage “patina” is no longer an appropriate term (see 7.0 above).

Marble patina has essentially the same chemical composition as the material upon which it has been laid and is formed in the same way as stalagmites – that is, the dissolution and redeposition of calcium carbonate by rain. These deposits may be comparatively minute; however, a change of surface takes place in the form of a variation in texture, translucency or colour (ferric iron in the solution causes warm tones, and ferrous iron or copper cause cooler greenish tones). The porosity of patinated surfaces often causes them to retain coloured impurities that make the stone interesting. Where patina exists, it is an essential feature of old marble and should be retained. Cleaning with abrasives, sharp tools or acids of any kind could ruin the patina.

11.0 APPLIED COATINGS

Applied coatings include materials that seal and discolour the surface, such as paint, lacquer, linseed oil, silicones, bitumen, wallpaper and its adhesives and so on. They also include materials that may only discolour the surface, such as cement, lime and some colour washes. Water- or oil-based paints, form a skin on the masonry surface without being absorbed into the material. Cement and lime washes, normally water-based, are absorbed slightly into the surface. Silicon and other synthetic resin materials can act as moisture barriers, and some change formation after application. Linseed oil is a protective coating, which eventually turns brown due to oxidation, attracts dirt, hardens and becomes difficult to remove. Wallpaper adhesives are normally organic and water soluble. Lacquers and varnishes form a physical bond. Epoxies and urethanes can become yellowed and chalked on exterior exposures.

Applied coatings can weaken the masonry surfaces and lead to failure of the coatings themselves. Causes of such failure must be known in order to simplify removal, cleaning and repair.

Surface coatings frequently create an evaporation plane beneath the coating or within the masonry material. Thus the surface material may spall, carrying the surface coating with it. In many cases, failure of the surface coating is partially caused by subflorescence.

Coatings which seriously interfere with the passage of water vapour may force the vapour to condense behind the coating. The surface layer of the masonry material becomes saturated; if freezing rain occurs, the surface will spall.

12.0 ORIENTATION AND LOCATION OF MASONRY SURFACES

12.1 ORIENTATION

Two important factors relating to the orientation of a historic structure are wind and thermal stress.

12.1.1 Wind

Wind contributes to masonry deterioration caused by rising damp and crystallization of soluble salts. High winds around the masonry surface cause evaporation to take place more rapidly than can be accommodated by the pores of masonry. Consequently, recrystallization takes place inside the pores of the material. Rapid evaporation draws moisture from the ground causing higher levels of rising damp.

Strong winds can create a sand blast effect which is destructive to masonry, especially to soft stone. Moderate winds can also be destructive, especially when air is polluted with coarse particulate matter.

The wind loading is directly proportional to the building height. It also is affected by the angle at which the wind strikes the building plane. An overpressure (loading) is created at the point of contact with the building wall. An underpressure (suction) is created at the opposite wall and, to a certain extent, at side walls.

12.1.2 Thermal Stress

Since stone is a poor conductor of heat, masonry surfaces exposed to the sun during the day get warmer than the inside mass. At night, radiation reverses this condition, creating a constant cycle of differential thermal stress between the surface and the mass. This effect is "further exaggerated by shaded areas" (Sneyers and DeHanau 1968). Such thermal stress causes fatigue of the material and results in minute fissuring and granulation of the stone. As particles of stone decompose, they form wedges in the fissures and the stone surface eventually spalls.

At a microscopic level, temperature changes can cause expansion and contraction of crystals in the stone matrix. The resultant tensile stresses can lead to fracture of the stone.

Colder areas attract moisture, while warmer areas allow moisture to evaporate. This causes the movement of moisture with soluble salts and leached soluble constituents of the material from cold to warm areas.

Temperature influences the conditions that promote hydrolysis in masonry, such as the amount of moisture in pores, the solubility of salts and the chemical reactions of dissolved gases. Hydrolysis is said to double with every 10° rise in temperature (Sneyers and DeHanau 1968).

12.2 LOCATION

The location of masonry surfaces affects the degree of disfiguration or deterioration.

Masonry surfaces near areas experiencing rising damp or moisture saturation, attract dust, soot and dirt easily. These pollutants mix with the moisture on the surface or in the air and, through chemical reaction or physical alteration, create a crust which may protect hard stone, but which may cause blistering and exfoliation on soft stone.

On masonry surfaces protected by projections and overhangs, surface skins form as a result of acidic sulphur gases forming sulphate and later attracting soot and smoke particles. These particles darken the area and attract more free acids and soluble salts in vapour from the atmosphere creating hard impermeable skins that blister and exfoliate (see 7.1 above). Skin formation does not occur on limestone in areas exposed to rain. The rain washes away the pollutants preventing skin formation.

Masonry surfaces located near the ground may suffer from the effects of plants and plant roots (see 8.1 above).

Masonry adjacent to copper roofs is subject to oxidation stains. Acids in the atmosphere also cause the formation of copper carbonate and copper sulphate, which are greenish. Eventually, copper carbonate stabilizes, but copper sulphate does not. Consequently the latter stains are most abundant in industrial areas (see 9.2 above).

Masonry located in urban areas experiences different conditions from rural areas. In cities, the mean temperature is 10 percent higher than in rural areas, even though city masonry experiences approximately 15 percent less solar radiation. Precipitation is 10 percent higher in cities, and fog frequency

is 30 percent higher in cities in summer and 100 percent higher in winter due to abundant condensation nuclei from dust and smoke.

Reduced sunshine and affected windspeed due to high-rise obstacles cause stone surfaces to dry slowly. This leads to moisture damage resulting in flaking and chipping.

13.0 SPECIALISTS AND CONSULTING SERVICES

The following is a partial list of specialists and consulting services available in the analysis of surface deposits, stains and decay for treating and cleaning masonry.

Individuals:

- N.R. Weiss, Scientific Consultant Preservation Program,
Columbia University, New York, NY.
- E.M. Winkler, Prof. Department of Earth Sciences,
University of Notre Dame, South Bend, IN.
- M.E. Weaver, Restoration Consultant, Ottawa, ON.
- D. Nicastro, M. Arch., Restoration Consultant, Toronto,
ON.
- T. Stambolov, International Centre for the Preservation
and the Restoration of Cultural Property (ICCROM),
Rome, IT.
- J.R.J. van Asperen de Boer, ICCROM, Rome, IT.

13.1 SCIENTIFIC RESEARCH ORGANIZATIONS

- National Research Council of Canada, Ottawa, ON.
- Conservation Division, National Historic Parks and Sites,
Ottawa, ON.
- Canadian Conservation Institute, National Museums of
Canada, Ottawa, ON.

14.0 BIBLIOGRAPHY

- Baker, I.O.** 1891. *A Treatise on Masonry Construction*. 5th edition. John Wiley & Sons, New York.
- Bullock, O.** 1971. *The Restoration Manual*. Silvermine Publishers Incorporated, Norwalk, CT.
- Conservation of Historic Stone Buildings and Monuments, Committee on.** 1982. *Conservation of Historic Stone Buildings and Monuments*. National Academy Press, Washington, DC.
- Conservation of Stone and Wood Objects, New York Conference on.** 1970. *Conservation of Stone*. Vol. 1, 2nd edition. 1971. International Institute for Conservation of Historic and Artistic Works, London.
- d'Amours, G.** 1984. "La Maçonnerie: Bibliographie et Références." (EA-PC-84-04). Unpublished report prepared for the Atelier des techniques de restauration, Les Fortifications de Québec. Heritage Conservation Program, Canadian Parks Service, Ottawa.
- Dukes, W.H.** 1972. "Conservation of Stone: Causes of Decay," *Architects' Journal*, Vol. 156, No. 34, pp. 429-32.
- Insall, D.W.** 1972. *The Care of Old Buildings Today: A Practical Guide*. The Architectural Press, London.
- Mamillan, M.** 1970. *Pathology of Building Materials*. ICCROM, Rome.
- Melville, I.A., and I.A. Gordon.** 1973. *The Repair and Maintenance of Houses*. The Estates Gazette Ltd., London.
- Nelson, Lee.** 1963. *Early American Brick Masonry and Restoration of Exterior Brick Walls*. Historic Structures Training Conference, Philadelphia, PA. U.S. Dept. of the Interior, Washington, DC.
- Plenderleith, H.J.** 1956. *The Conservation of Antiquities and Works of Art*. Oxford University Press, London.
- Shaffer, R.J.** 1972. *The Weathering of Natural Building Stones*. Reprint of 1932. The Building Research Establishment, Garston, near Watford, UK.
- Skater, G.** 1973. *A Review of Natural Stone Preservation*. National Bureau of Standards, Washington, DC.
- Sneyers, R.V., and P.J. DeHanau.** 1968. *The Conservation of Stone*. The Conservation of Cultural Property. UNESCO, Paris, pp. 209-35.
- Stambolov, T., and J.R.J. van Asperen de Boer.** 1972. *The Deterioration and Conservation of Porous Building Materials in Monuments: A Literature Review*. ICCROM, Rome.
- Timmons, S., ed.** 1976. *Preservation and Conservation: Principles and Practices*. Proceedings of the North American International Regional Conference, Williamsburg, VA and Philadelphia, PA. 1972. The Preservation Press, Washington, DC.
- Winkler, E.M.** 1973. *Stone: Properties, Durability in Man's Environment*. Springer Verlag, New York.

Illustrations are the property of the Heritage Conservation Program, unless otherwise noted.

VOLUME VI

CONSERVATION OF MATERIALS

3.1

MORTAR

COMPOSITION AND PROPERTIES

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: C. LEVESQUE

CONTENTS

1.0 INTRODUCTION

2.0 DEFINITIONS

3.0 TYPES OF MORTARS

3.1 MUD MORTARS

3.2 GYPSUM MORTARS

3.3 LIME MORTARS

3.3.1 Historical Uses

3.3.2 Types of Limes

3.3.3 Methods of Slaking

3.4 COMMON LIME MORTAR

3.4.1 Preparation Methods

3.4.2 Setting and Hardening of Common Lime Mortars

3.5 HYDRAULIC LIME MORTARS

3.6 POZZOLANA MORTARS

3.7 NATURAL CEMENT MORTARS

3.8 PORTLAND CEMENT MORTARS

3.8.1 Historical Development

3.8.2 Modern Portland Cement

3.9 MASONRY CEMENT MORTARS

3.10 CONTEMPORARY MORTAR MIXES

3.10.1 General

3.10.2 Portland Cement-Lime Mortars

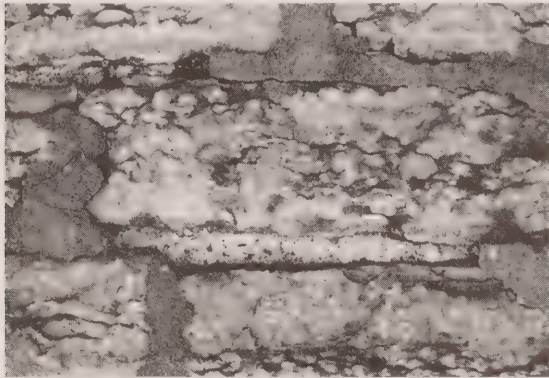
3.10.3 Portland Cement-Masonry Cement

4.0 BIBLIOGRAPHY

1.0 INTRODUCTION

This article provides basic information about mortar composition and properties for personnel engaged in the investigation, conservation and maintenance of historic structures containing mortar.

Previously some historic masonry or log structures had been inadequately analysed and conserved because of the lack of a convenient reference work describing the different types of mortar that were used in the past and may be available today. This article attempts to provide such a reference and to cover the basic types of mortar binders used in Canada. For the composition and properties of aggregate or building stones see Section 3.2 "Mortar: Deterioration."



Cracking and Spalling

2.0 DEFINITIONS

Mortar is a mixture of a binder, an aggregate and water, used to hold masonry units such as stones or bricks. It can also be used as chinking for log structures.

Mortar performs several essential functions. The plastic nature of fresh mortar permits it to fill voids between masonry units that do not exactly fit together and to gradually become adjusted to movements within a wall that occur during construction. Mortar helps make walls watertight; it enables bricks and small stones to form a coherent mass and it acts as a lubricant to permit the sliding of heavy stones into position. The form and colour of mortar joints contribute significantly to the appearance of a wall.

It is essential to distinguish between *hard* and *soft* mortars. The use of lime sand mortar predominated until about 1880. It was soft enough to furnish a plastic cushion that allowed bricks or stones some movement relative to each other. The entire structural system depended upon some flexibility in the masonry components of a building. A cushion of soft mortar furnished sufficient flexibility to ... compensate for uneven settlement of foundations, walls, piers and arches; gradual adjustment over a period of months or years was possible. In a structure that lacks flexibility, stones and bricks break, mortar joints open and serious damage results.

Cement mortars used after about 1880 are hard. Joints of cement mortar are strong and unyielding; they are appropriate to modern bricks and concrete blocks. Rigidity is characteristic of modern masonry. Those accustomed to cement mortar and concrete must consider the elasticity of historical masonry when restoring historic buildings. Hard and soft building materials cannot be used together effectively.

Several properties must be considered when judging the appropriateness of a particular mortar: cohesiveness, adhesiveness, strength, setting time, hardening time, handling ease, ability to set and harden underwater (*hydraulic* quality) and the degrees of expansion and solubility. The visual aspects of colour and texture are also of significance (McKee, p. 61).

3.0 TYPES OF MORTARS

3.1 MUD MORTARS

The oldest mortar used for building was mud, and it is still used in many countries throughout the world. In ancient Egypt mud mortar was used with sun-dried bricks, but for bedding the stonework of monumental buildings, gypsum was used.... Clay or mud, usually with chopped straw or reeds, but sometimes without, was used from the earliest times, and still survives all over the Middle East as the traditional type of mortar (Davey, p. 120).

In America, clay mortar was used for ordinary brick and stone walls in regions where lime was difficult to obtain. Often, clay was used because of its low cost.

Clay mortar joints can bear heavy loads, but in humid climates, they need protection from rain; ... mud and clay strengthened by straw or hog's hair was used for mortar as late as about 1790.... Old interior chimneys are commonly found to have been constructed with clay mortar below the roof line; above that level they were pointed with lime mortar....

3.2 GYPSUM MORTARS

The earliest known use of gypsum mortar was in ancient Egypt, where mortar of fluid consistency was poured into narrow joints to fill them and used to lubricate the bed of large stones while they were being moved into position. Gypsum mortar has been used in Persia from ancient times to the present. In medieval France, gypsum mortar was used to bond small stone members when they were required to support unusually heavy loads. In the United States, gypsum was sometimes used to set marble trim and tiles and as a minor ingredient in lime and cement mortar (McKee, p. 61).

3.3 LIME MORTARS

3.3.1 *Historical Uses*

Lime mortars were the most common type used in structures until the 20th century. It is known that lime was used as early as 4000 B.C. in Egypt for plastering. The Great Wall of China was largely laid with lime mortar. However, it was the Romans who most fully developed its structural uses in ancient times. Historical records show that Vitruvius, a military engineer under Julius Caesar, even wrote a specification on lime for use as mortar in stone and clay brick masonry.

Historically, lime was formed by burning pure limestone (calcium carbonate) at less than 1000° C. to convert it into quicklime (calcium oxide). When water was added to quicklime, slaked or hydrated lime (calcium hydrate) was formed.

3.3.2 *Types of Limes*

Because limestone is of sedimentary origin, its composition varies with the circumstances of sedimentation. Therefore, there are four broad types or groups of limes:

- (a) non-hydraulic limes, high calcium limes or 'fat' limes produced from carboniferous and pure oolitic limestone and white chalk;

- (b) semi-hydraulic or moderately hydraulic limes from grey chalk, siliceous limestones, and argillaceous limestones (containing clayey matter – alumina and silica, in the form of a hydrated aluminium silicate);
- (c) hydraulic limes from lias limestone and chalk marl;
- (d) magnesium limes from magnesium limestone including dolomite (with up to 40 percent magnesium carbonate).

Group (a) produces a white lime, which when slaked and used in mortar can only gain strength very slowly by taking up carbon dioxide from the atmosphere and so reverting extremely slowly to calcium carbonate. Such mortar has very little strength, and is described as non-hydraulic. Some other limestones, for example, those in groups (b) and (c), on the other hand, contain materials in addition to calcium carbonate, such as silica and alumina in various forms. The limes produced from these limestones are called hydraulic limes and mortars made from them gain considerably in strength. These semi-hydraulic or hydraulic limes, or cements, will set under water. Their quality depends on the relative proportions of calcium carbonate, silica, and alumina present in the raw materials, the care taken in preparing and blending the raw materials; and the temperature at which they are burnt or calcined. When the lime is hydrated, the silica and alumina present will combine with it to form insoluble compounds of cementitious value such as calcium silicates and calcium aluminates (Davey, p. 97-8).

3.3.3 *Methods of Slaking*

There are four methods of slaking lime:

- (1) *Sprinkling or drowning*. The correct amount of water was sprinkled onto quicklime. The lumps cracked open and dry powder was formed.
- (2) *Immersion*. Quicklime was placed in a basket, lowered into water and drawn up in time to complete the slaking action in the air. The correct time of immersion was a critical factor which was difficult to determine.
- (3) *Exposure*. Quicklime was simply exposed to the air in a shed or shelter for a considerable length of time. It absorbed moisture from the air and became partially slaked, but it also absorbed carbon dioxide

and thus acquired inert material (calcium carbonate) that adulterated the slaked lime. This method was universally considered the least satisfactory one.

(4) *Making lime paste.* Quicklime was placed in a pit or a vat and more water than the amount required for slaking was poured over it; the mixture was allowed to stand and slake. This lime paste was either used at once or stored in a covered pit for months or years.

When quicklime is slaked, the increase in volume varies according to the kind and amount of impurities that are present. Therefore, the quantity of quicklime needed to make mortar of a desired quality varied; it was necessary to know the properties of the lime from each source in order to establish the correct ratio of lime to sand and water....

Fat limes absorb about one-half their volume in water during slaking and increase greatly in volume. Mortar made from fat lime was preferred by masons because of its "rich" or "oily" consistency. Meagre or poor limes absorb less water, give off less heat during slaking, and yield a smaller quantity of mortar. However, some meagre limes impart desirable properties to mortar that make it useful in damp locations (McKee, pp. 63-64).

Until 1905 all lime used for structural purposes was lump quicklime that was slaked on the job in metal troughs or in pits or trenches dug into the earth... *pulverized quicklime*, slaked on the job, would be the lowest-cost building lime in high putty yield and material cost. Because it is pulverized, slaking proceeds much more rapidly than the old lump type. In spite of this, it has lost favor because of the inconvenience of slaking and the danger of burns to workers...

Before 1940, in the United States all building *hydrated limes* has to be soaked in large metal troughs, for 12-24 hr to develop plasticity. As such, the lime was used as a putty on the job. Then *autoclaved hydrated lime* was introduced. This type of lime develops high plasticity without soaking so that it can thus be fed dry into the mortar-mixer, like cement or gypsum (Boynton, p. 448-49).

3.4 COMMON LIME MORTAR

3.4.1 Preparation Methods

The common variety of mortar was made of lime, sand and water. Details of its preparation varied according to regional customs and individual preferences but most of these details were well-known throughout Europe and America.... Mortar was prepared for use by the following basic methods:

- (1) Dry pulverized quicklime and dry sand were mixed. Water was then added and the whole mass was mixed.
- (2) Dry sand was added to lime paste and thoroughly mixed in. If necessary, water was added.
- (3) Slaked lime powder, sand and water were mixed together, either simultaneously or by adding water to previously mixed lime and sand.

Examples of these general methods and modifications of them follow. The descriptions include the relative proportions of lime to sand:

Sand is added to lime for economy and to prevent shrinkage. Sand should be... in such quantity that the lime will fill all the interstices. If an excess of sand is used, the bond is poor. If too little sand is used, the mortar shrinks and cracks. If too little lime is used the paste is made thin. In ordinary sands, the spaces form 39% to 40% of the total volume, and in such 1 vol. paste fills voids of 2-1/2 vol. sand. In practice, 1.25 to 2 vol. of sand to 1 of paste is used. This in case of fat lime means 3 to 5 vol. of sand to 1 measured vol. of lime. This gives a plastic mortar which does not crack (Ries and Eckel).

Vitruvius was an ancient Roman architect whose books were widely quoted and whose precepts were highly respected in Europe and America. He recommended the following proportions:

... mix your mortar, if using pitsand, in the proportions of three parts of sand to one of lime; if using river or sea-sand, mix two parts of sand with one of lime.... Further, in using river or sea-sand, the addition of a third part composed of burnt brick, pounded up and sifted, will make your mortar of a better composition to use. (Vitruvius, reprint 1960).

Loriot was a French engineer of the 18th century whose knowledge of mortar was widely acclaimed by engineers in England and America. His formula was made public in 1774:

... take one part of brick dust finely sifted, two parts of fine river-sand skreened, and as much old slaked lime as may be sufficient to form mortar with water in the usual method, but so wet as to serve for the slaking of as much powdered quick-lime, as amounts to one-fourth of the whole quantity of brick-dust and sand. When the materials are well mixed, employ the composition quickly, as the least delay may render the application of it imperfect or impossible (Partington).

... Thorough mixing or beating was emphasized by most authorities. In 1823, Peter Nicholson recommended a practice in *The New Practical Builder* which was probably well agreed upon in England and the United States.



Use of Mortar, Trowel and Board

Before the mortar is used, it should be beaten three or four times over, so as to incorporate the lime and sand, and to reduce all knobs or knots of lime that may have passed the sieve. This very much improves the smoothness of the lime, and, by driving air into its pores, will make the mortar stronger: as little water is to be used in this process as possible. Whenever mortar is suffered to stand any time before used, it should be beaten again, so as to give it tenacity, and prevent labour to the bricklayer. In dry hot summer weather, use your mortar soft; in winter,

rather stiff. If laying bricks in dry weather... wet your bricks by dipping them in water, or by causing water to be thrown over them before they are used... (Nicholson 1823; McKee, pp. 64-65).

3.4.2 *Setting and Hardening of Common Lime Mortars*

After being mixed, common lime mortar remains plastic for several hours. It must be placed in the wall while in this condition. Mortar is said to have set when it loses its plasticity. When set, it will support the load of masonry placed on it if the work does not proceed too rapidly. After setting, mortar hardens at a slow rate, taking months or years to attain its ultimate strength. Sometimes common lime mortar on the interior of thick walls never really hardens (McKee, pp. 64-65).

Samples of lime mortar have been taken from walls of ancient buildings which were only 50 to 80 percent saturated with carbonic acid after an exposure of more than 2000 years.

Mortar sets and hardens approximately as follows: As mortar dries, some of the hydrated lime crystallizes and binds the mass together; this constitutes setting. Hardening takes place largely when carbon dioxide from the air combines with hydrated lime in the mortar to form calcium carbonate. This does not occur if the mortar is either too wet (containing more than five percent water) or too dry (containing less than seven-tenths of one percent water). Mortar at the surface of a joint hardens first; the interior hardens only to the extent that carbon dioxide in solution or in gaseous form can reach it by penetrating the pores of the material (McKee, p. 65).

If lime mortar was to be used in the interior of thick walls, the addition of a saccharine substance was sometimes beneficial. Saccharine matter unites with lime to form sucrate of lime, a solid which possesses considerable strength, dissolves freely in water, and is acted upon by carbonic acid. The sucrate of lime being stronger than the carbonate, will add to the strength of the mortar; and as the lime will unite with the sugar more rapidly than with the carbonic acid in the air, the sugar will also cause the mortar to set more quickly; but the sucrate of lime being soluble in water will in time be washed out by the rain. Therefore, the addition of a saccharine substance to mortar is most beneficial in a dry climate, as can be found in India. Moreover, the compounds of lime with sugar are at-

tacked by the carbonic acid in the air, and hence the strengthening effect of the sugar is not permanent when exposed to the weather. Owing to these facts, the use of sugar with lime mortar is not of much practical value.

3.5 HYDRAULIC LIME MORTARS

Hydraulic lime is obtained by calcining a limestone containing silica and alumina to a temperature short of incipient fusion to form sufficient free lime to permit hydration (slaking) and at the same time leaving unhydrated sufficient calcium silicates to provide hydraulic properties. As shown in the table included in VI.3.2, there are two classes of hydraulic lime, according to their amount of hydraulic energy:

- a. moderately hydraulic lime, containing from 10 to 20 percent clay matter, slaking after an hour or two without crackling, and setting under water in six to eight days; and
- b. eminently hydraulic lime, containing from 20 to 30 percent clay matter, slaking very slowly and with great difficulty, and setting under water in 12 to 20 hours and becomes hard in two to four days.

"Early American builders probably used a great deal of weakly hydraulic lime without being aware of its identity. French engineers used hydraulic limes in civil construction during the 19th century" (McKee, p. 68)

However, since its strength has always been of much lower magnitude than cements and since it had slower setting qualities, it quickly lost popularity.

3.6 POZZOLANA MORTARS

The ancients discovered that they could also convert a non-hydraulic lime into a hydraulic or partially hydraulic one by adding suitable materials. Such additions, which we call pozzolanas, after Pozzuoli, the locality in Italy where a natural source of such material – a volcanic earth – exists, are those which, though not necessarily cementitious by themselves, possess the requisite compounds of silica and alumina which will combine with non-hydraulic or semi-hydraulic limes at ordinary temperature in the presence of moisture to form stable insoluble compounds of cementitious value, such as calcium silicates and aluminates. When mixed with lime mortar in addi-

tion to, or in partial substitution for, sand, they will impart hydraulic properties and greater strength. Pozzolan materials fall into two categories: (a) natural and (b) artificial.

(a) Natural:

Italian Pozzolanas, e.g. from around Pozzuoli, near Naples, Civita Vecchia, and around Rome.

Santorin Earth from the Greek island of Santos.

Trass composed of pumice fragments from Andernach on the Rhine in Germany, and from Bavaria.

Volcanic ash from deposits in southeast France, Azores, Teneriffe in the Canary Islands, and Japan.

Diatomaceous Earth including Kieselguhr, infusorial earth, diatomite, tripoli, and rottenstone, etc.

(b) Artificial:

Burnt shale, burnt diatomite or pumicite, burnt clay, e.g. homra (Egypt) and surkhi (India).

Powdered tile and potsherds.

Certain slags.

The clays and shales are burnt to a temperature varying between 600° and 950°C., the optimum temperature varying rather critically with different types of material....

It is clear that the knowledge of the use of lime mortar, and the benefits to be derived by adding pozzolan material, spread from Greece to Rome. This in turn led to radical changes in building construction. Not only was it possible to erect more slender walls with the stronger mortar, but the construction of arches and vaults became possible. The cement also offered good resistance to seawater and in consequence was extensively used for marine structures....

The Romans found that the volcanic clay or tufa consisting of clay and gravel, containing approximately 35 percent of soluble silica, from Puteoli in the bay of Naples, was excellent for producing hydraulic mortar.... The Romans called the material pulvis puteolanus. It is at present variously called puzzolana, pozzolan or pozzolana, and materials which possess similar properties have come to be described generally as pozzolan.... In addition to the natural material from Pozzuoli and elsewhere the Romans continued to use crushed brick and tile. It produced a mortar with very much the same characteristics, and its use seems to have been preferred for some specific purposes throughout the Empire,

and was, in fact, in some parts the only hydraulic cement available to them.

The Romans used these pozzolana mortars in positions where it was important to prevent the penetration of damp – for example, for lining the inner surfaces of channels, drains, baths, tanks, and aqueducts, for rendering walls in damp or exposed situations, for bonding masonry in waterlogged ground, for pavements, and for torching (sealing the spaces between) roofing tiles to prevent the penetration of driving rain....

In post-Roman times there seems to have been a reversion to the use of non-hydraulic limes, which were not so durable and in England it was probably not until the sixteenth and seventeenth centuries that imported pozzolana ('Dutch tarras' or trass) and lime mixtures were used; the usual mixtures for works exposed to the action of water being composed of 1 volume of trass to 2 volumes of slaked lime. The so-called Dutch tarras (terras or trass) was dug at Andernach, Bockenheim, and Frankfurt-on-Maine in Germany and transported down the Rhine to Holland where it was ground for mixing with lime mortars. The export trade was very considerable. In Holland the material was mixed with a hydraulic lime (blue argillaceous lime) made on the banks of the River Scheldt. A layer of this lime, about 1 foot in thickness, was spread on the ground and moistened with water and covered with a layer of trass of the same thickness. After two or three days, the material was thoroughly mixed together and well beaten, and left for a further two days before use. The cement so produced the famous 'tarras mortar' used in Holland for the construction of sea defences and for aquatic work (Davey, p. 102-3).

Although historical records show that 40 tonnes of pozzolanic materials were imported from Europe to the United States in 1796 for the construction of canal locks in Massachusetts, it can be said that pozzolana mortars were never extensively used in North America.

3.7 NATURAL CEMENT MORTARS

Towards the end of the eighteenth century and in the first half of the nineteenth century a great need was created for dependable hydraulic cements. Firstly, the London Building Act of 1774 (14th of Geo. III) drafted by Sir Robert Taylor, architect of the Bank

of England, gave great encouragement to the use of stucco as the Act virtually prohibited the use of exposed timber details on buildings, and laid down that external ornaments to fronts of buildings were to be of brick, stone, burnt clay, artificial stone, stucco, lead, or iron. Secondly, the great industrial revolution which was breaking on the country called for development of internal communications, canals, roads, bridges, tunnels, docks and harbours, and eventually railways. Great engineering works had to be carried out, and hydraulic cements which would resist the penetration of water were needed for their successful completion.

In 1796 James Parker of Northfleet discovered that he could make a hydraulic cement by calcining the nodules of argillaceous limestone, called 'septaria', 'cement stones', 'rock stones' or 'noddles', which were derived from the Tertiary clay beds and found lying along the foreshore of the Thames Estuary (Davey, p. 104).

These rocks contained between 45 to 64 percent calcium carbonate and up to 55 percent of clay, silicon and other impurities. Parker called the product "Roman Cement," a misnomer, but nonetheless a name by which it is still known.

Parker's product enjoyed a good reputation in Europe and America for several decades. He recommended making mortar by mixing two measures of water with five of Roman cement. This mortar set quickly (in 10 to 20 minutes), a quality that was considered a disadvantage. After Parker's patent expired, Roman cement was widely manufactured by others, who used cement rock obtained at several places in England and Boulogne pebbles found at Boulogne, France....

After 1819, all masonry used in the construction of the Erie Canal was laid in natural cement mortar. Various sources afford different information about the mortar mix; apparently one part of sand was mixed with two parts of cement. The general practice in New York State in about 1840 was to mix two or three parts of sand to one of cement...

By 1837, natural cement was manufactured at Rosendale, New York. Shortly thereafter natural cement rock was also discovered in other localities and the widespread manufacture of natural cement began.

Natural cement mortar was used mainly in areas where masonry was subjected to moisture and great strength was required.... Natural cement shrank in volume when water was added; masons did not like the "feel".... However, natural cement was sometimes used as an additive to lime mortar, to which it contributed strength and durability (McKee, pp. 68-69).

When the supply of septaria nodules dredged from the foreshore diminished, the cement manufacturers resorted to the artificial blending of suitable clays with chalk, finely ground together, in the proportions of 1 1/2 to 2 of clay to 1 of chalk. These were calcined and then re-ground, but the temperature of calcining was not so high as that needed later to produce Portland cement, which also contained a higher proportion of chalk (Davey, p. 105).

3.8 PORTLAND CEMENT MORTARS

3.8.1 Historical Development

In 1811 James Frost patented a hydraulic cement very much like that made previously by L. J. Vicat (1786-1861) in France by calcining an intimate mixture of limestone (chalk) and clay which he ground together in a wet mill. The temperature of calcining was not high and the resulting product was considered to be inferior to Parker's Roman cement. In 1822, however, Frost took out a further patent (British Patent No. 4679) for a hydraulic cement in which the calcining was carried out at a higher temperature, high enough in fact to drive off all the carbon dioxide in the mixture. He called his new product 'British Cement' and it gained a better reputation in England and America than his earlier cement did.

To produce the modern Portland cement the same ingredients of chalk and clay are used, but the temperature of calcining is high enough to sinter or vitrify the material to form a clinker which is subsequently ground to a fine powder. It has long been a matter for discussion as to when and by whom cement of this type was first produced. Certainly Vicat and Frost were progressing along the right lines, and so was Joseph Aspdin (c. 1779-1855) of Leeds, a bricklayer who took out a patent (British Patent No. 5022) in 1824, and to whom most credit for the invention of Portland cement is given, and he was the first to call the cement 'Portland'. Aspdin described his method of making the cement as follows:

... I take a specific quantity of limestones such as that generally used for making or repairing roads, and I take it from the roads after it is reduced to a puddle or powder; but if I cannot procure a sufficient quantity of the above from the roads, I obtain the limestone itself, and I cause the puddle or powder, or the limestone, as the case may be to be calcined. I then take a specific quantity of argillaceous earth or clay, and mix them with water to a state approaching impalpability, either by manual labour or machinery. After this proceeding I put the above mixture into a slip pan for evaporation, either by the heat of the sun, or by submitting it to the action of fire or steam conveyed in flues or pipes under or near the pan till the water is entirely evaporated. Then I break the said mixture into suitable lumps, and calcine them in a furnace similar to a lime kiln till the carbonic acid is entirely expelled. The mixture so calcined is to be ground, beat or rolled to a fine powder [Aspdin] (Davey, pp. 106-7).

3.8.2 Modern Portland Cement

Modern Portland cement is made from one of the following mixtures:

- (i) high calcium limestone or chalk and clay or shale, giving a mixture with about 65 to 75 per cent of calcium carbonate, the rest being aluminium silicate and free silica;
- (ii) argillaceous (clayey) limestone, or cement rock either alone or mixed with high calcium limestone;
- (iii) blast-furnace slag and limestone.

These raw materials are finely ground either dry or wet, and then sintered at a temperature of about 1300° to 1450°C. When ground to a fine powder and mixed with water the cement sets very quickly, too quickly in fact, for it to be of much use. A small amount of gypsum is added to the cement clinker during grinding and this acts as a retarder. Present-day methods of manufacture are most highly developed, and controlled carefully at every stage to ensure a very uniform product of high quality...

Towards the end of last century it was found that granulated blast-furnace slag had hydraulic properties and could be used as an addition to Portland cement. The slag occurs in molten form in the pro-

duction of pig-iron in blast-furnaces, and it is granulated by quenching rapidly in water. If slowly cooled the slag has no hydraulic properties. The granulated slag is normally added to the Portland cement clinker and the two materials are finally ground together.

In England, the cement is called Portland-blast-furnace cement and contains up to 65 per cent of granulated slag. In the United States of America the cement is called Portland-blast-furnace-slag cement, and contains not more than 70 per cent of slag.... In France and Belgium, cements with up to 30 per cent of granulated slag are called *ciment de fer*, and *ciment de haut fourneau* with up to 70 per cent of granulated slag. The French also use a cement called *ciment de laitier au clinker*, which has no more than 20 per cent of Portland cement clinker and the rest slag (Davey, pp. 108, 110).

The introduction of Portland cement undoubtedly did a great deal to revolutionize the construction industry.

It immediately captured the interest and imagination of architects and builders that this gray powder could be mixed with sand, graded aggregate, and water and produce in a few days materials of rock-like strength – much harder than the old Roman cements and lime-pozzolan mixtures. In contrast, pure lime mortars only develop strength very slowly through carbonation of the lime from CO_2 in the atmosphere. Final strength today is about 35-40 times less for lime than cement. Furthermore, this small budding cement industry had the foresight to organize and develop uniform standards of quality, something that the lime or lime-pozzolan industry had to that time never achieved. It was possibly easier for the Portland cement industry to accomplish this standardization since the product was a heterogeneous mixture or blending of limestone and siliceous materials in precise proportions in contrast to pure or hydraulic limes, largely derived from one given stone deposit. Any cement producer unable to meet the specification developed by the Portland cement industry through its association, could not label its product *Portland cement*. In time, most aspiring cement manufacturers saw the wisdom of complying with these early standards (and later modifications). The result was amazing industry solidarity, which led to the formation of a strong association that pursued vigorously research, development, and promotion.

Although lime on the average had produced eminently satisfactory mortars and had centuries of durability experience, architects soon increasingly specified Portland cement for mortars, apparently on the premise that the hardest and strongest mortars were best. Cement's strength and speed in setting had been amply demonstrated in the many types of poured concrete structures that were rapidly becoming the vogue in construction. Strength became the keynote. The first transition was toward mixtures of cement and lime in varying volumetric proportions ranging widely from 1:3 to 3:1 cement and lime, respectively. During this period, even most of the strongest adherents of cement recognized the need of a plasticizer, like lime, to produce a workable mortar.... In spite of many conflicting opinions and theories among builders as to which specified mix produced the optimum-quality mortar, the trend, abetted by the momentum of this new, exciting industry and its persuasive (sic) promotion, was for increasing proportions of cement....

3.9 MASONRY CEMENT MORTARS

But the mortar strength complex among builders, nurtured by the cement industry, continued to grow until in the 1915-1930 era many builders were using either straight cement or mortars with only 10-25 % lime as an admix to the cement by volume. Shortly after this change in mortar practice, there was an epidemic of leaky masonry in many cities.... Masonry work with these mortars was studied during construction. It was discovered that the mortars lacked plasticity; they worked lean and harshly under the trowel and did not spread easily. As a result, joints were often not completely filled; there was not intimate contact between the mortar and masonry unit; often the mortar stiffened ("pancaked") prematurely owing to the rapid suction or removal of moisture by the absorptive brick or concrete block from the mortar – all of which contributed to *poor bond* at the mortar interface and subsequent cracking and leaks.

These research findings caused the pendulum to swing back to lime in the 1930s and the high-strength complex on mortars was subdued. Mortars of 1:1:6 – 1:2:9 (cement, lime, and sand, respectively) by volume generally prevailed during this period. Such mortars had

more than ample strength, had high plasticity, were quick-setting owing to the cement content, and provided watertight walls with strong bond.

However, lime's resurgence was short-lived. The cement industry introduced a new cementitious material for masonry – proprietary mixtures, called “masonry cements,” “patent mortars,” or “mortar mixes.” Although these mixtures varied in components and proportions, the prevailing products were largely mixtures of 40-60% Portland cement, 40-60% pulverized limestone, and a fractional percent of air-entraining agents or stearates. The latter organic chemical additives were used in lieu of lime to provide plasticity that was not obtained with the former high Portland cement mortars. By diluting the Portland cement with pulverized limestone, the compressive strength of the resulting mortar was greatly reduced from straight cement mortars, with their objectionably high brittle strengths. Obviously, too, from the cement producer's standpoint, there was great economy in using the low-cost pulverized limestone and air-entraining agent combination.... A few of these patent mortars contained lime, instead of limestone, but usually these were blast-furnace slag-lime mixtures, with or without some Portland cement....

Since about 1958, there has been a slight tendency for cement companies to add hydrated lime to their masonry cements, most of which products formerly contained no lime. For many masonry cements to develop high plasticities equivalent to lime-cement mortars, increasingly larger amounts of air-entraining agents were added by the cement manufacturers to the point that the resulting mortars contained 18-25% air. Although research has clearly proven that entrained air improves the weatherability of mortars, other research has shown that bond strength of mortar suffers as the air content increases, particularly when air contents exceed 15%. Consequently, some cement companies started altering their mortar composition by reducing the air-entraining agent so as to produce a 15-18% maximum range of air in the mortar. The resulting loss in plasticity was restored by substituting 5-10% hydrated lime (in place of the pulverized limestone) [Boynton, pp. 442-45].

3.10 CONTEMPORARY MORTAR MIXES

3.10.1 General

... CSA Specification A-179 includes five types of mortar permitting combinations of either Portland cement and lime, or Portland cement and masonry cement....

Type M mortar contains predominantly Portland cement and has high compressive strength. Types S, N, O and K mortars contain progressively higher proportions of lime or masonry cement. Minimum strength values for each type are shown. Although strength values decrease through mortars M to K, workability and water retentivity increase. The specification requires a minimum water retention of 70 percent (Davison, pp.162-63).

3.10.2 Portland Cement-Lime Mortars

Figure 1 in CSA Specification A-179 indicates the wide range of properties for the cement-lime mortars listed. At the one extreme, a predominantly cement mortar has a high compressive strength and a low water retentivity. A wall containing this mortar will be very strong but may be vulnerable to rain penetration. At the other extreme, lime mortar has low compressive strength and high water retentivity. A wall containing it will have lower strength, particularly early strength, but it should be much more resistant to rain penetration.

Between the two extremes, various combinations of cement and lime can provide a wide variety of properties – the “best of two worlds” – the high strength and early setting characteristics of cement modified by the excellent workability and water retentivity of lime. A designer who has clearly established his objectives should have no problem in identifying the mortar he wants by referring to Figure 1. The point at which the two curves cross, designating the mortar with the highest compressive strength compatible with optimum water retentivity, lies within the boundaries of a Type N mortar. This explains the extensive use of the 1:1:6 cement-lime mortar.

No discussion of cement-lime mortars is complete without mentioning their self-healing capability. In this process, sometimes referred to as autogenous healing, lime carried in solution in water moving through the masonry is deposited in cracks and crevices when the water evaporates. Successive deposits eventually fill the cracks.

3.10.3 Portland Cement-Masonry Cement

Masonry cement mortars generally have excellent workability and moderate strength. Small bubbles of entrained air contribute to the roller-bearing action and can, in fact, provide good workability with poorly graded aggregates. Increasing air content levels, however, are accompanied by decreasing compressive strength and, more important, by decreasing bond strength. This is a matter for concern because the specification does not contain a maximum air content value. Masonry cement mortars also have high sand-carrying capacities, and this feature is sometimes exploited to the detriment of the masonry. The addition of Portland cement to masonry cement mortars increases their strength so that they can qualify as Types M and S.

It is difficult to predict the properties of masonry cement mortars because their composition is not published and may be altered without notice. Their use should be based on a knowledge of local performance (Davison, pp. 163-64).

4.0 BIBLIOGRAPHY

American Society for Testing and Materials. 1978. *Annual Book of ASTM Standards*. Parts 13 and 16. ASTM, Philadelphia.

- Baker, I.O.** 1897. *A Treatise on Masonry Construction*. John Wiley & Sons, New York. Quoted material reprinted by permission: John Wiley & Sons, Inc.
- Boynton, R.S.** 1980. *Chemistry and Technology of Lime and Limestone*. John Wiley & Sons, New York. Quoted material reprinted by permission: John Wiley & Sons, Inc.
- Davey, N.** 1961. *A History of Building Materials*. Phoenix House, London.
- Davison, J.I.** 1974. *Masonry Mortar*. Canadian Building Digest, No. 163, Division of Building Research. National Research Council of Canada, Ottawa. Quoted material reprinted by permission: National Research Council.
- Hummel, A., and K. Wesche.** 1960. *Tests on Masonry Mortars*. Translated by D. A. Sinclair. NRC TT-887. National Research Council of Canada, Ottawa. Originally from Fortsuhn U. Forchungen in Bauwesen, Ser. D, (24), 1956, pp. 15-31.
- Levesque, C.** 1984. *Bref Historique des Mortiers de Maçonnerie*. Report EA-PC-84-07, Architecture and Engineering, Canadian Parks Service, Ottawa.
- McKee, H. J.** 1973. *Introduction to Early American Masonry, Stone, Brick, Mortar and Plaster*. National Trust for Historic Preservation and Columbia University, Washington, DC. Quoted material reprinted by permission: Copyright 1973, National Trust for Historic Preservation in the United States.
- Millar, W.** 1905. *Plastering, Plain and Decorative*. B.T. Batsford, London.
- Nicholson, P.** 1823. *The New Practical Builder*. Thomas Kelly, London.
- Ritchie, T., and J. I. Davison.** 1964. *Cement-Lime Mortars*. Technical Paper No. 183. Division of Building Research. National Research Council of Canada, Ottawa.
- Partington, C. F.** 1825. *The Builder's Complete Guide*. Sherwood, Gilbert and Piper, London.
- Phillips, M. W.** 1974. "SPNEA-APT Conference on Mortar, Boston, March 15-16, 1973," *Bulletin of the Association for Preservation Technology*, Vol. 6, No. 1, pp. 9-39.
- Ries, H., and E. C. Eckel.** 1901. *Lime and Cement Industries of New York*. Albany, New York.
- Vitruvius.** 1960. *The Ten Books on Architecture*. Translated by Morris Hicky Morgan. Reprint. Dover, New York.

Illustrations are the property of the Heritage Conservation Program, unless otherwise noted.

VOLUME VI

CONSERVATION OF MATERIALS

3.2

MORTAR

DETERIORATION

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: SUTER KELLER INC.

TABLE OF CONTENTS

1.0 INTRODUCTION

- 1.1 SCOPE
- 1.2 DEFINITIONS
- 1.3 GENERAL DISCUSSION

2.0 TYPES OF MORTAR DETERIORATION

- 2.1 CRACKING
- 2.2 DISINTEGRATION
- 2.3 SPALLING
- 2.4 DISCOLOURATION AND STAINING
- 2.5 EROSION
- 2.6 ETCHING

3.0 MECHANISMS OF MORTAR DETERIORATION

- 3.1 ALKALI-AGGREGATE REACTION
- 3.2 CRYSTALLIZATION OF SOLUBLE SALTS
- 3.3 CARBONATION
- 3.4 CORROSION OF EMBEDDED METALS
- 3.5 CHEMICAL ATTACK
- 3.6 LEACHING OUT OF FREE LIME
- 3.7 FROST ACTION
- 3.8 THERMAL MOVEMENT
- 3.9 FOUNDATION MOVEMENT
- 3.10 MOISTURE MOVEMENT
- 3.11 OVERLOADING

4.0 SOURCE OF MORTAR DETERIORATION

- 4.1 ADMIXTURES AND ADDITIVES
- 4.2 CEMENT
- 4.3 AGGREGATES
- 4.4 MIXING WATER
- 4.5 MOISTURE
- 4.6 ATMOSPHERIC GASES
- 4.7 TEMPERATURE
- 4.8 ORGANIC GROWTH
- 4.9 DESIGN AND CONSTRUCTION DETAILS
- 4.10 WORKMANSHIP
- 4.11 MAINTENANCE AND REPAIR

6.0 BIBLIOGRAPHY

1.0 INTRODUCTION

Mortar, an integral part of masonry construction, serves as the material which binds the masonry units together to form a monolithic mass. Any deterioration of the mortar will therefore also impair the performance of masonry as a whole.

Hundreds of masonry structures (which are of historic importance) exist all across Canada. Hundreds are also being built, as interest in masonry has been revived, due to a better understanding of the engineering aspects of the material. In order to preserve the existing structures and to ensure a long life of the structures now being built, it is essential to know the types and causes of mortar deterioration.



Mortar Deterioration

The purpose of this article is to identify the common types of mortar deterioration and to briefly explain the basic mechanisms responsible for deterioration. The primary deterioration sources originating from constituent materials, environmental factors and building practice are also discussed. The

article is intended for use by staff and consultants responsible for the investigation, preservation, restoration and maintenance of masonry structures. While this article may serve as a source of basic knowledge on mortar deterioration and a diagnostic aid to the investigation of mortar deterioration problems, services of specialists such as petrographers, chemists and material scientists may be required to address some of these problems.

1.1 SCOPE

Mortar is mainly used in masonry construction as a joint material. This article deals with the deterioration of mortar in masonry joints. Plasters, pargings and renderings are excluded although their deterioration problems often are closely related to those of the jointing mortar.

Only lime and Portland cement based mortars are considered. Mortars using epoxy and other organic binders may have additional deterioration problems which are not included here.

1.2 DEFINITIONS

Carbonation: a slow chemical reaction between atmospheric carbon dioxide and cement paste which hardens the exposed surfaces of cement products and reduces their permeability. Carbonation is accompanied by some shrinkage.

Efflorescence: the deposit of salt crystals, usually whitish grey but sometimes also green, at the exposed surfaces of masonry, concrete and other cement based products.

Alkali-aggregate Reaction: an expansion chemical reaction between certain types of aggregates and the alkali in cement paste.

Frost Action: a process of deterioration of porous materials such as mortar and concrete by alternate freezing and thawing of water locked in the material; the process is often referred to as freeze-thaw action.

Expansion Joint: a separation in structural elements, such as walls, to allow small relative movements caused by, for example, temperature and moisture changes.

Control Joint: a continuous joint to regulate the location and amount of cracking and separation in structures resulting from movements caused by temperature and moisture changes and by differential foundation settlements.

1.3 GENERAL DISCUSSION

Mortar deterioration is affected by a complex interplay of constituent materials, environmental factors and building practice. Portland cement-based mortars have many deterioration problems in common with concrete since the binding material is the same. However, before the advent of Portland cement, mortars using pure lime as the binding material were widely used in masonry construction. These mortars, although weak in strength, did not display some of the deterioration problems of today's Portland cement-based mortars. In contemporary masonry construction, a wide range of proportions of the basic ingredients of mortar is used. The composition and properties of both historic and modern day mortars are treated in Section 3.1.

Environmental factors such as moisture and temperature play a key role in mortar deterioration. Mortar and masonry units are inherently porous and thus absorb moisture from the environment. As will be discussed later, moisture is by far the most important agent of mortar deterioration. The climate of Canada aggravates moisture-related problems through frost action, one of the most damaging mechanisms of mortar deterioration.

Most deterioration problems can be linked directly or indirectly to aspects of building practice including design and construction details, workmanship and maintenance. For example, poor details of flashing and damp-proof courses may promote moisture penetration and ensuing moisture-related problems.

The various primary sources and mechanisms of mortar deterioration as well as the types of deterioration are illustrated in Table 1. How these primary sources, mechanisms and effects are interlinked is also shown in the table. This illustration can serve as a ready reference for the source-mechanism-effect relationship of mortar deterioration. The most common types of mortar deterioration are described in .2 below while the mechanisms of mortar deterioration are covered in .3 below. The primary sources which make up these mechanisms are treated in .4.

2.0 TYPES OF MORTAR DETERIORATION

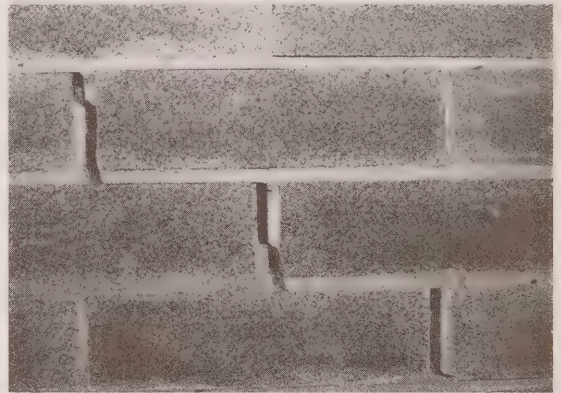
The most common types of mortar deterioration are described in the following sections. For convenience, these so-called deterioration effects are listed in Table 1.

2.1 CRACKING

Cracks are almost invariably present in mortar joints. Since in masonry construction the bond interface between masonry units and mortar is typically the weak link, restrained masonry movements, uneven foundation settlements and other factors commonly cause cracking at the interface.

Cracking often is restricted to the mortar joint itself. Very fine cracks, caused by drying and carbonation shrinkage, may be hardly visible at early stages of deterioration. Crazeing, a pattern of very fine, randomly occurring cracks, is typically caused by aggravated carbonation or differential moisture movement

Cracking contributes to other types of deterioration such as disintegration, spalling, and efflorescence by allowing more water to permeate the masonry. The additional ingress of water combined with the harsh Canadian climate in turn speed up the deterioration process.



Stepped crack in historic clay brick masonry illustrates the fact that the bond between the mortar and masonry unit is typically the weak link. The mortar, although cracked, is still in good condition.

2.2 DISINTEGRATION

This type of deterioration is evidenced by the presence of randomly oriented cracks, as well as by bulging and loosely bound mortar. It can be caused by various mechanisms such as frost action, chemical attack, alkali-aggregate reaction, organic growth, crystallization of soluble salts and corrosion of embedded metals. Mortar disintegration can be closely linked to deterioration of masonry units.

2.3 SPALLING

Similar to the case of concrete spalling dealt with earlier in 1.2, mortar spalling is the separation of mortar from the surface in slivers or small slices. Since it is closely linked to cracking and disintegration, it is shown as a subeffect in Table 1.

2.4 DISCOLOURATION AND STAINING

Discolouration of mortars may be caused by chemical attack and acid wash. A brown stain is usually caused by corroded ferrous metal embedded in the mortar. Stains of a brown oily appearance may be caused by the manganese used to colour bricks. Mortar joints remaining damp and shaded for long periods of time may exhibit signs of moss growth in the rainy season. Upon drying, this moss may leave a blackish stain on the mortar.

The most common type of stain is a whitish-grey stain referred to as efflorescence. Efflorescence per se is primarily an aesthetic problem. It is caused by the crystallization of water-soluble salts on the surface as the water evaporates out, and is easily removed by rainwater. When the source of salt is internal, i.e., the salt is present within the mortar, the problem may disappear in time. However, if the salt is derived from an external source such as alkaline earth, the problem may be permanent. Efflorescence is usually at a peak during the late winter months when the rate of evaporation of moisture is high. Efflorescence is a sign that salts are present. For problems associated with soluble salts, see 3.2 below.

2.5 EROSION

This deterioration is characterized by the loss of mortar from its surface by abrading mechanical agents such as a strong flow of water, sandstorms, sandblasting and human and other traffic. Since mortar joints are usually softer than masonry units, these agents erode mortar comparatively more than the masonry units.

2.6 ETCHING

Etching is a superficial damage characterized by a roughening of the mortar surface. It is caused by acidic solutions derived from various sources. Etching reduces the weather-tightness of mortar joints thus contributing to further water-related deterioration of mortar.



The soft lime mortar placed in the joints over 150 years ago has been extensively eroded by rain runoff aided by frost action.

3.0 MECHANISMS OF MORTAR DETERIORATION

As shown in Table 1, a large number of mechanisms cause mortar deterioration. The lines connecting mechanisms to effects indicate, for instance, that cracking, disintegration and spalling can be linked to many potential mechanisms. Nevertheless, moisture movement and frost action are the most important contributors to mortar deterioration in the Canadian climate.

The following sections describe each of the mechanisms listed in Table 1.

3.1 ALKALI-AGGREGATE REACTION

Although aggregates are generally believed to be an inert filler material in mortars, certain chemical reactions take place between aggregates and cement-lime. Chemical reactions between some types of aggregates and the alkali in cement paste can cause expansion of mortar, generating a disruptive force which can lead to crazing and disintegration. Three types of alkali-aggregate reaction have been reported to date. Alkali-silica reaction, the earliest one to be discovered, involves siliceous

aggregates. A second type, alkali-carbonate reaction, involves carbonate aggregates. A third type, reported to have occurred in some locations in Canada, is called alkali-silicate reaction. In general, alkali-aggregate reactions occur only in the presence of moisture and are accelerated by an increasing alkali content in the cement paste and by increased temperature.

3.2 CRYSTALLIZATION OF SOLUBLE SALTS

Many kinds of water soluble salts are present in the mortar itself and in the masonry units. Such salts are also carried into the mortar by moisture originating from the soil. These salts include sulphates, carbonates and silicates of sodium, potassium, calcium and magnesium.

Ordinary Portland cement is a source of sulphates of sodium and potassium. As the moisture evaporates, these salts crystallize and may form a usually whitish deposit on the exterior surface of mortar or masonry units; the effect is commonly known as efflorescence. A more serious type of damage or disintegration can occur when growth of the crystals takes place within the pores near the surface of the mortar joints. This process is destructive because crystallization of the salts is accompanied by a volume expansion. During the late winter months, the rate of evaporation of moisture in many parts of Canada is high; therefore, problems emanating from crystallization of salts are at a peak during that time.

3.3 CARBONATION

The chemical reaction between atmospheric carbon dioxide and Portland cement products is generally known as carbonation. Carbonation shrinkage, amounting to as much as one-third of the total shrinkage, often leads to a network of fine cracks called "crazing" on the surface of thick mortar joints. Carbonation can also decrease the alkalinity of the system, thus promoting corrosion of reinforcing bars and metal anchors embedded in the mortar.

3.4 CORROSION OF EMBEDDED METALS

Corrosion of ferrous metals not only decreases the capacity of the reinforcement or anchors embedded in mortar but also causes disintegration and cracking of mortar. This is because rust, the product of the process of corrosion, occupies more than twice the volume of the iron and can thus exert a disruptive force of large magnitude. Corrosion is an electrochemical process and needs water to form the electrolyte. A galvanic

cell causing corrosion may be formed between two dissimilar metals coupled in the same electrolyte or between two similar metals coupled in different electrolytes. It is the latter type which is of prime importance to the corrosion of metals in mortar. Different electrolytes may emanate from different concentrations of moisture, oxygen or dissolved substances existing from point to point of the same metal bar or anchor.

3.5 CHEMICAL ATTACK

Soluble sulphates present in mortar aggregates, masonry units and mixing water, or carried by water originating in soil, can react with tricalcium aluminate present in ordinary Portland cement. The reaction products have a greater volume than the reactants; thus a disruptive force is developed, sometimes causing serious disintegration of mortar. However, sustained wetting is generally necessary for this sulphate attack to cause appreciable mortar damage.

Mortar is not resistant to strong solutions of sulfuric, sulfurous, hydrochloric, nitric, or hydrofluoric acids. A prolonged contact with these acids may lead to etching and disintegration of mortar. These acids may be derived from chemical combinations of water with gases, such as sulphur dioxide present in industrial environments, or from soil in contact with the structure.

Contact with salt-laden air near oceans or with de-icing salts may promote crystallization of salts as previously discussed in 3.2 above.

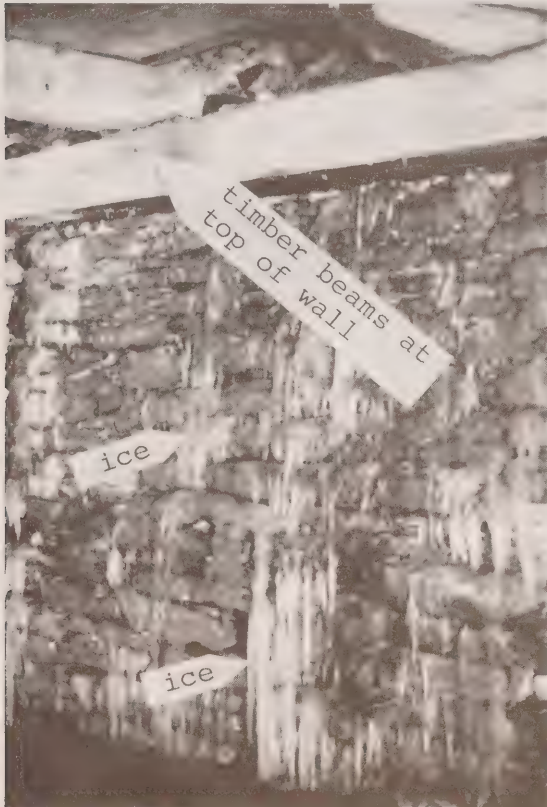
3.6 LEACHING OUT OF FREE LIME

All cement products contain some uncombined or free lime. Water, particularly when mildly acidic, can leach out this free lime from mortar. This weakens the gel structure of the cement paste and can leave a white deposit at the surface of the structure.

3.7 FROST ACTION

Under Canadian climatic conditions, frost action is the foremost mechanism leading to mortar deterioration over the long term. Both mortar and masonry units are porous materials which take up (and give off) moisture at varying rates depending on their permeability, the existence of prior cracks, and other factors. When such porous materials containing varying water contents are subjected to freezing, the water

undergoes a volume expansion of about nine percent. This can produce large internal pressures which in turn lead to mechanical damage and cracking of the porous material. Repetition of freezing and thawing of the moisture present in mortar and masonry units, commonly known as frost action or freeze-thaw action, may cause serious damage to the masonry. Since masonry structures in the Canadian climate typically are exposed to many freeze-thaw cycles in a year, the long-term destructive effects of frost action on mortar and masonry units cannot be overemphasized.



Interior surface of basement level stone masonry wall in late winter. Backfill to the top of the wall on the exterior is not free-draining and allows large amounts of moisture, aided by the fill sloping towards the wall, to reach the moisture. Frost action over many decades has led to the disintegration and erosion of the mortar throughout the thick wall section such that an ice build-up as shown is possible.

For porous materials subjected to freeze-thaw action, Litvan has presented an overview of the factors which affect durability. Fontaine's recent field work dealing with the Quebec City fortification walls in turn provides a direct application of freeze-thaw durability principles to mortar exposed to the Canadian climate. While the interested reader dealing with a mortar deterioration problem should consult both of these excellent references for details, it is useful to summarize key observations related to frost action of masonry:

"The severity of mechanical damage is directly proportional to the water content of the porous solid" (Litvan). In practice, the degree of masonry saturation will of course depend on many factors including the masonry exposure conditions (vertical vs. horizontal surface, protective overhangs, orientation) and climatic conditions.

While an increasing number of freeze-thaw cycles will significantly contribute to masonry deterioration, the number of cycles do not appear to be as important as the thermal gradient or cooling rates. This indicates that masonry in the Canadian climate will deteriorate most rapidly in regions where both the cooling rate is high and a large number of freeze-thaw cycles take place annually. Fontaine has identified Quebec City as one such region.

Masonry exhibiting either very high or very low porosity will generally perform well when subjected to frost action. Examples of very high and very low porosity materials would be clay brick and marble, respectively. Where high porosity is present, moisture is able to move relatively quickly so that pressure buildup due to freezing is reduced; in the case of low porosity, less moisture is present. Mortar typically can be classified as a material of intermediate porosity and hence must be judged as frost-susceptible.

Frost action on mortar is aggravated by the presence of de-icing salts. These salts increase the number of freeze-thaw cycles over a cold season and also increase the supply of water for penetration into the mortar by melting ice and snow.

Damage due to frost action can be reduced by the judicious use of air-entraining admixtures in the mortar mix. These admixtures can entrain air in the mortar in the form of a very large number of well-dispersed tiny air bubbles. These air bubbles are largely impermeable to water but act as reservoirs for water migrating under pressure due to the freezing of water in larger pores.

Freezing of fresh mortar during construction in cold weather can be detrimental, particularly if too much water and masonry units of low absorption, are used. As in all good quality masonry construction, the proper matching of a masonry unit's absorption characteristics with the appropriate mortar is essential for obtaining an initial bond which will ensure reasonable frost resistance of the mortar.

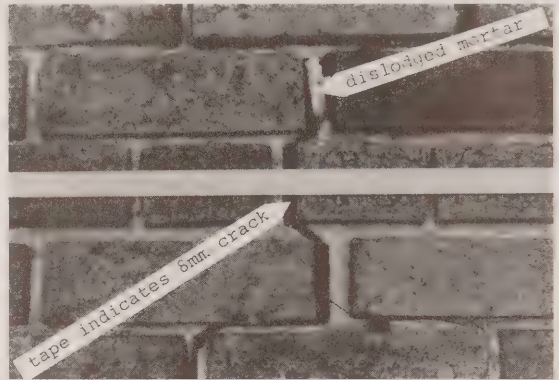
Damage to mortar and masonry due to frost action typically progresses from exterior surfaces towards the interior. As described by Fontaine, a major exception are fortification walls where moisture held in soil embankments is able to reach the back of such walls and cause additional frost damage.

In the foregoing discussion, little differentiation was made between mortar and masonry units. The two materials were discussed jointly because firstly, both are porous materials to which the observations regarding frost action apply, and secondly, deterioration of one material may affect degradation of the other material. If the mortar is more frost-susceptible than the unit, mortar cracking and crumbling may cause spalling and cracking of masonry units at least in the vicinity of mortar joints. The opposite may occur if the masonry unit is more frost-susceptible. Typically, the bond at the interface between mortar and masonry units is the weak link in masonry construction. Frost action working on this weak link may cause local bond failure which, together with pre-existing cracks and voids at this interference, will allow moisture to penetrate more deeply into the masonry section. As a result of the initially minor cracking, an increased supply of moisture will reach regions further away from exterior surfaces; this will allow the deterioration due to frost action to accelerate until more major damage will necessitate remedial measures such as repointing the masonry.

3.8 THERMAL MOVEMENT

Like most other materials, mortar undergoes a volume change with a change in temperature. Thermal stresses leading to cracking, particularly at the interface between mortar and masonry units, can occur when there is a significant difference in coefficients of thermal expansion between mortar and masonry units and the temperature range is large. Since coefficients of thermal expansion of North American masonry materials vary considerably and Canadian temperature ranges are quite large, thermal stresses are significant and probably cause extensive fine cracking. Such initial fine cracking will be enlarged with time due to frost action and additional thermal cycles.

Another major cause of thermally induced cracking is restraint of thermal movement of a masonry element or structure. Restraint may be affected by the foundation, intersecting walls, roof or structural elements of other materials being rigidly attached to the masonry. Again, initial fine cracking will become more serious due to the ingress of moisture, frost action and additional thermal cycles.



An initially narrow crack has widened to about 8 mm due to frost action and cyclic thermal movement. The mortar is cracked in many locations and is disintegrating.

3.9 FOUNDATION MOVEMENT

Differential foundation settlement and other foundation movements are a major cause of masonry cracking. Since the bond between mortar and masonry units typically is the weakest link in masonry construction, mortar joint cracks occur. Again, once the cracks are present, accelerated mortar deterioration can take place.

3.10 MOISTURE MOVEMENT

Moisture affects mortar and masonry structures in four major ways: the first pertains to mortar shrinkage, the second to clay brick expansion, the third to capillary canals in the mortar, and the fourth to moisture migration due to a thermal gradient.

The volume of cement paste in mortar varies with its water content. Mortar shrinks upon hardening and swells slightly when rewetted. However, a large part of the shrinkage that occurs in a fresh mortar due to drying is irreversible. This initial drying shrinkage increases with increasing cement paste

and total water content of the mortar mix; it typically amounts to about 0.05 percent. Depending on the rate of drying, this shrinkage can cause transverse cracks in mortar joints, as well as bond cracks at the mortar-masonry unit interface.

The moisture expansion of clay bricks is generally attributed to the hydration of amorphous materials or glasses that have formed during the firing operation. Brick moisture expansion varies greatly and takes place over many years. It affects mortar deterioration in that masonry cracking caused by moisture expansion will typically take place at the mortar-masonry unit interface. Ingress of moisture, frost action and continued moisture expansion of the clay brick will accelerate mortar disintegration.

Capillary canals are thought to form as the mortar hardens. To quote Fontaine:

The cement paste, as it sets or as it hydrates, has to eliminate the excess water which is not required for this chemical reaction. A production of capillary pores much smaller than the air voids then begins. These pores juxtapose and subsequently create capillary canals through which the excess water is discharged. As the mortar will have set, these canals will allow the running water to penetrate in the mortar. Therefore when frost occurs, the water inside these canals will become solid, with a 9% increase of volume. The resulting ice pressure will permanently damage the mortar by collapsing the canal walls.

This then represents another mechanism which can lead to mortar deterioration due to moisture movement.

Similar to the case of ice lens formation in soils, ice lenses can form in masonry elements due to moisture migration under a thermal gradient. Internal pressures associated with the build-up of ice lenses can be very destructive to non-frost resistant mortar (see Fontaine).

3.11 OVERLOADING

Masonry is strong in compression, and weak in tension. Since the compressive strength of masonry is relatively little influenced by the compressive strength of mortar and also since large factors of safety (of the order of five to ten) are present in most historic masonry constructions, mortar and masonry cracking due to compressive overloading is very rare. Cracking due to compressive overloading typically is associated

with stress concentrations and bearing distress. For example, the placement of a steel beam during rehabilitation of a masonry structure can create local bearing distress due to stress concentration. Also, mortar and masonry units in a particular structure may have deteriorated, due to various mechanisms, to the stage where relatively uniform compressive loading is no longer present; resultant stress concentrations can then lead to additional cracking of mortar and units.

Masonry cracking is commonly caused by load effects which cause excessive tensile stresses. Since the bond interface between mortar and masonry units typically is the weakest link in masonry construction, cracks frequently occur at the interface. Overloading to cause such tensile cracking often is associated with lateral load and eccentric load effects. An example of lateral load effects would be embankment pressure of frost-susceptible soils acting against masonry fortification walls. Eccentric loads cause tension whenever the load acts outside the cross-section's kern points. Since for a rectangular wall cross section, the kern points are only one-sixth of the wall thickness away from the wall centreline, eccentric compressive loads frequently cause tensile cracking.

4.0 SOURCE OF MORTAR DETERIORATION

As indicated in Table 1, a number of sources of mortar deterioration interact with various mechanisms to produce the final effects seen in the field. For the Canadian climate, the key sources of deterioration are moisture and temperature. This is shown in Table 1 where nine of the eleven mechanisms are influenced by these two sources.

The following sections describe each of the sources listed in Table 1.

4.1 ADMIXTURES AND ADDITIVES

Many admixtures are commercially available for use in concrete and mortar mixes. Many of these admixtures, while improving certain desirable properties of mortar, cause adverse effects on others. Calcium chloride, mainly used as an accelerator, reduces the resistance of mortar to sulphate attack, but also aggravates alkali-aggregate reactions and increases shrinkage and creep. Some water-retaining additives of organic origin may become acidic after decomposition causing disintegration of mortar.

4.2 CEMENT

Portland cement contains alkali: both in soluble and insoluble forms. The soluble portion, to a large extent sulphate and varying between 10 and 60 percent of the total alkali content, is mainly derived from the fuel used in the cement production. The insoluble portion is derived mainly from clay and other siliceous components of the raw cement mix. Experience in the United States indicates that the destructive expansion due to alkali-aggregate reaction does not occur if the alkali content of cement is lower than 0.6 percent. Cements containing very fine materials such as natural pozzolanas, blast furnace slags and fly ash react with aggregates to a lesser degree than ordinary cements.

High-alkali cements have also been found to promote efflorescence.

4.3 AGGREGATES

Many aggregates are called reactive in that they react expansively with the alkali in cement pastes. The minerals that are responsible for alkali-silica reaction include opal, chert, flint, tridymite, volcanic glasses and microcrystalline quartz. Aggregates from argillaceous dolomitic limestone are susceptible to alkali-carbonate reaction. Greywacks, argillites and phyllites containing vermiculites cause the alkali-silicate reaction.

Aggregates containing soluble sulphates and carbonates of sodium, calcium, magnesium and potassium can also cause efflorescence and disintegration problems.

4.4 MIXING WATER

Sodium chloride and magnesium sulphate in sea water, when used as mixing water in mortar, react with calcium aluminates in the cement to form complex salts and alkali hydroxides promoting the alkali-aggregate reaction. Sea water used as mixing water also promotes corrosion of reinforcement and anchors by impairing the protective film normally present on steel. Mixing water derived from alkaline soils provides added alkali for reaction with reactive aggregates.

4.5 MOISTURE

Moisture causes a greater proportion of deterioration in mortar than any other single source. Wetting of mortar leads to a

slight increase in its volume; eventual drying of the mortar leads to shrinkage, often resulting in very fine cracks. Excess water present in the mortar joints leaches out the soluble salts of calcium, magnesium and sodium, leaving crystalline and whitish deposits at the surface commonly known as efflorescence. Excess water can also leach out the free lime present in the mortar matrix, weakening the gel structure. Sustained wetting of mortar promotes sulphate attack. Moisture promotes carbonation, leading to fine cracks in the mortar joints and increased corrosion of steel anchors, ties and other reinforcement embedded in mortar. Moisture locked in porous mortar joints can freeze in winter and, through expansion, build up a disruptive force sufficient to cause disintegration and spalling of mortar.

4.6 ATMOSPHERIC GASES

Air in industrial environments may contain sulphur dioxide, carbon dioxide, chlorine, hydrogen chloride, fluoride, bromide and iodide gases. All these gases dissolve in water to form acids which can cause slow disintegration of mortar. Carbon dioxide in the presence of water also promotes carbonation leading, to crazing and increased corrosion of reinforcement.

4.7 TEMPERATURE

Many adverse effects on mortar are caused and promoted by both high or low temperature. High temperature increases the rate of corrosion of embedded metals and many chemical processes which attack mortar. Fluctuations of temperature with excursions below the freezing point cause alternate freezing and thawing of saturated mortar leading to disintegration. Significant temperature-induced stresses can develop in mortar in temperate climates causing cracks in the relatively weak mortar joints.

While the intense heat of a fire dehydrates the calcium silicate hydrate and the calcium hydroxide in the cement paste, the resultant strength loss in the mortar is often not as severe as might be expected. This is so, firstly, because the generally massive masonry walls in historic masonry construction do not absorb heat quickly during a fire and, secondly, because there is seldom enough fuel available to keep a fire burning for many hours at high temperatures. Fire damage to mortar in massive masonry walls is therefore generally restricted to areas near exposed surfaces and can be repaired by deep repointing.

4.8 ORGANIC GROWTH

Although damage caused to mortar by bacteria and fungi are uncommon in a Canadian climate, higher organisms such as lichens and plants can cause deterioration of mortar. The metabolic products of lichens are acidic and thus can cause etching of mortar. The aerial roots of creepers, like ivy, can dislodge mortar from masonry joints and create increased moisture paths.

4.9 DESIGN AND CONSTRUCTION DETAILS

Many mortar deterioration problems are directly or indirectly caused by poor design and construction details. Lack of a proper damp-proof course above the foundation allows moisture from the soil, frequently laden with alkalis and salts, to penetrate into the mortar joints. Inadequate flashing details can keep mortar joints saturated long enough to make them vulnerable to frost action and can cause increased corrosion of reinforcement. Poor air and vapour barrier details can lead to condensation and eventual freezing of water in the mortar joints of exterior walls in buildings. Lack of expansion and control joints at appropriate locations can lead to unnecessary cracking or overstressing due to thermal, moisture and foundation movements. Use of ungalvanized ties aggravates the corrosion problem.

4.10 WORKMANSHIP

Since masonry construction is labour intensive, many problems can originate from poor workmanship. Partial filling of joints and deep furrowing result in leaky mortar joints, giving rise to many water-related problems. Properly designed flashing and venting details are often poorly constructed, such as when weep holes are omitted and flashing is discontinuous. Too much mixing water to improve workability can result in porous mortar joints. Untooled or improperly tooled joints contribute to poor weathertightness. Hydrochloric acid, often used to clean freshly mortared masonry, may be an additional source of chloride efflorescence and may weaken the bond strength of mortar. When impure, it may also later stain the mortar by the deposition of iron compounds. Use of high absorption masonry units with inadequate pre-wetting results in weak mortar joints. On the other hand, pre-wetting of units to saturation results in porous mortar joints.

4.11 MAINTENANCE AND REPAIR

Lack of timely maintenance measures is a key source of mortar deterioration. Initially fine cracks are able to enlarge due to other sources such as moisture combined with freeze-thaw cycles. The enlarged cracks in turn admit moisture more liberally and the deterioration process speeds up.

Improper maintenance and repair measures can contribute to new and increased deterioration problems. Use of hard mortar or mortar not compatible with masonry units can cause spalling and cracking.

Many cleaning agents, mostly acidic solutions, are used to remove different stains from masonry surfaces; such solutions can cause disintegration and etching of mortar joints, particularly if not washed away thoroughly after cleaning.

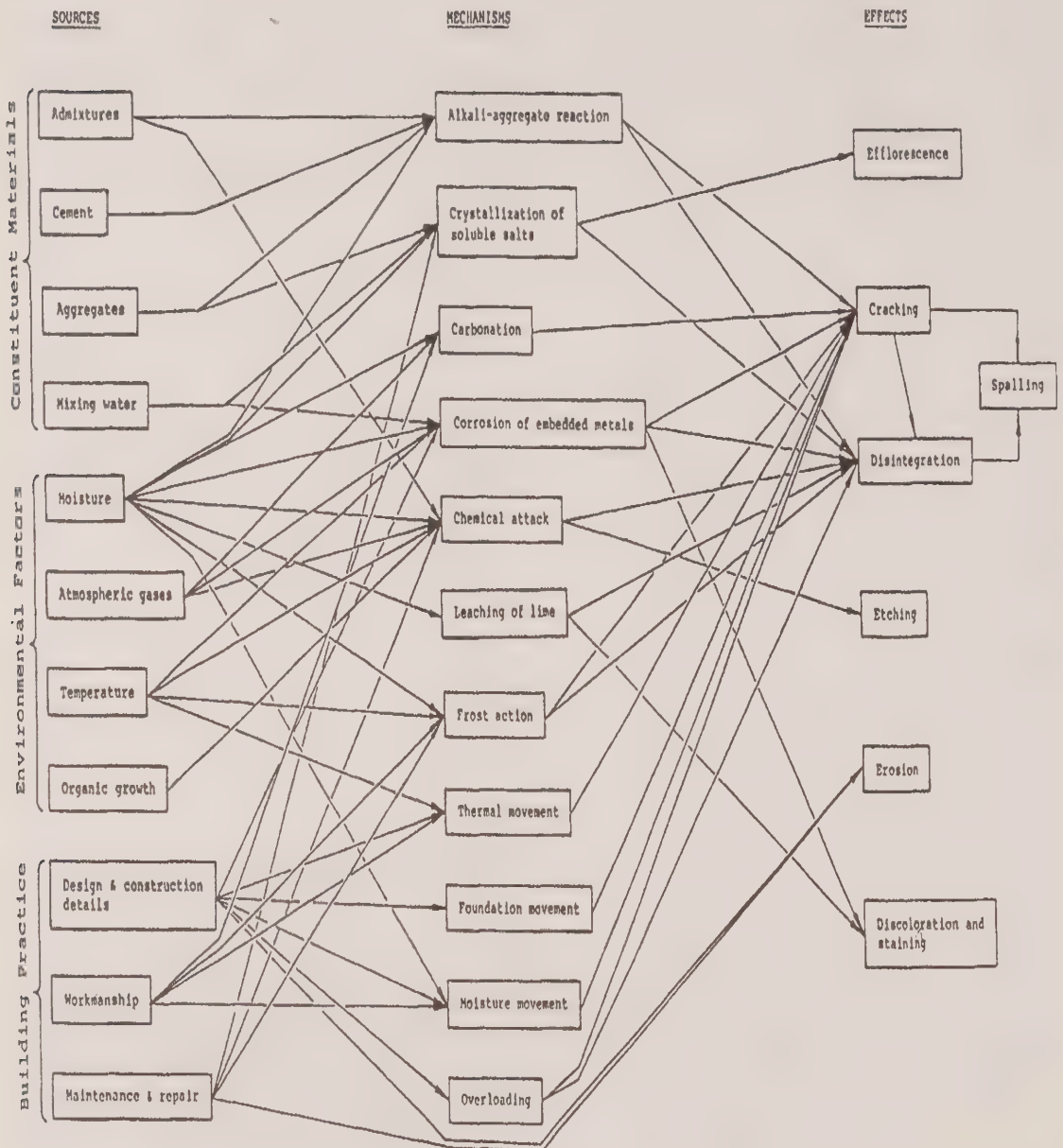
A popular technique for cleaning masonry surfaces is sandblasting. Most masonry units are hard enough to withstand sandblasting without being eroded. However, mortar joints and many old masonry units such as sand-lime bricks may be seriously eroded by indiscriminate sandblasting.

Surface coatings are sometimes used in the preservation of historic buildings to repel water from masonry surfaces. Such coatings, including silicones which are reputed to breathe, can trap water for a sufficient time to freeze and cause serious spalling of both mortar and masonry units. These coatings may also force the crystallization of salts to occur within the surface pores, again leading to spalling. Further, surface coatings can discolour with time and thus initiate a staining problem. Masonry is a permeable material which can take up and give off moisture. Any maintenance and repair measures must preserve the ability of masonry to breathe.



Result of Sandblasting Masonry

TABLE 1: THE SOURCE-MECHANISM-EFFECT RELATIONSHIP OF MORTAR DETERIORATION



6.0 BIBLIOGRAPHY

American Concrete Institute. 1968. *Durability of Concrete Construction*. Monograph No. 4

Contains details on freezing and thawing, alkali-aggregate reaction, corrosion of embedded metals, chemical effects, and other durability aspects of concrete which may also be common to mortar.

Fontaine, A. 1985. "Durability of Masonry Mortar in a Nordic Climate," *Bulletin of the Association for Preservation Technology*, Vol. 17, No. 2. Quoted material reprinted by permission: © APT.

Contains an in-depth discussion of the mechanism of frost action on masonry mortar and the role of various factors on this action.

Litvan, G.G. 1980. *Freeze-thaw Durability of Porous Building Materials*. ASTM Special Technical Publication No. 691. Philadelphia. Quoted material reprinted by permission: © ASTM.

For porous building materials subjected to frost action, this paper summarizes experimental observations and outlines a theory to explain durability behaviour.

Phillips, M.W. 1973. *Summary of the SPNEA-APT Conference on Mortar*. Boston.

Contains summaries of topics such as stability and chemical consolidation of mortar and various other aspects of mortar related to preservation.

Ramachandran, V.S., R.F. Feldman and J.J. Beudoin. 1981. *Concrete Science*. Division of Building Research, National Research Council of Canada. Heyden and Son Ltd.

Contains in-depth studies on the microstructure of cement paste, chemical admixtures, alkali-aggregate reaction, frost action, carbonation shrinkage and sea water attack on concrete which may also be common to mortar.

The following publications deal with efflorescence problems in masonry:

Brick Institute of America. 1969. *Efflorescence Causes*. Technical Note No. 23. Rev. (December).

National Concrete Masonry Association. 1977. *Control and Removal of Efflorescence*. TEK No. 92.

Ritchie, T. 1960. *Efflorescence*. Canadian Building Digest No. 2, February, Division of Building Research. National Research Council of Canada, Ottawa.

The following publications discuss the harmful effects of coatings and cleaning methods on masonry mortar:

Ashton, H.E. 1970. *Coatings for Masonry Surfaces*. Canadian Building Digest No. 131, Division of Building Research. National Research Council of Canada, Ottawa.

Brick Institute of America. 1977. *Cleaning Brick Masonry*. Technical Note No. 20. Rev. (September-October).

Ritchie, T. 1974. *Silicone Water-Repellents for Masonry*. Canadian Building Digest No. 162, Division of Building Research. National Research Council of Canada, Ottawa.

VOLUME VI

CONSERVATION OF MATERIALS

4.1

METALS

DETERIORATION OF CAST AND WROUGHT IRON

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: A. POWTER

CONTENTS

1.0 INTRODUCTION

2.0 BIBLIOGRAPHY

1.0 INTRODUCTION

Cast and wrought iron can deteriorate and fail in a number of ways, some related to the inherent properties of the material itself and others to the way in which it is fabricated and used. The identification of the material and the problem at hand can be even more complicated. It is necessary for the conservationist to know what investigation methods are available and what deterioration processes are occurring so that the right consultants can be engaged and the correct questions can be asked of them.

The references listed in this bibliography have been selected to assist conservation professionals faced with deteriorated cast- and wrought-iron components. It is not exhaustive. It includes the principal and most useful current books and articles that contribute to a clear understanding of the subject.



Deterioration of Wrought Iron

2.0 BIBLIOGRAPHY

- Alexander, W., and A. Street.** 1976. *Metals in the Service of Man*. Penguin, London.
- Anon.** 1976. "Weak Iron Clue to Tay Bridge Disaster," *New Civil Engineer* (Jan). Reprint from Edinburgh Newspaper, Dec. 1879.
- Arup, Ove Partnership.** n.d. Notes on Materials. No. 39. *Graphitisation of Cast Iron*. No. 44. *Re-use of Structural Cast Iron*.
- Bakhvalou, G.T., and A. V. Turkouskaya.** 1965. *Corrosion and Protection of Metals*. Pergaman Press, Oxford.
- Blackwell, A.** 1976. "Notes on the Restoration of the Ironbridge." Unpublished. Salop County Council, Highways and Transport Dept.
- _____. 1975. "The Restoration of the Ironbridge." Unpublished. by Salop County Council, County Bridge Engineer.
- Britton, S.C.** 1958. *Anti-Corrosion Manual*. Science Surveys Ltd., London.
- Chilton, J.P.** 1968. *Principles of Metallic Corrosion*. Royal Institute of Chemistry, London.
- Chong, C.V.Y.** 1977. *Principles of Metallic Corrosion*. Macdonald & Evans, Plymouth.
- Davey, A. et. al.** 1978. *Care and Conservation of Georgian Houses*. Paul Harris publishing with Edinburgh Newtown Conservation Committee, Edinburgh.
- Diamant, R.M.E.** 1971. *Prevention of Corrosion*. Business Books Ltd., London.
- Evans, U.R.** 1963. *An Introduction to Metallic Corrosion*. Edward Arnold, London.
- _____. 1972. *The Rusting of Iron: Causes and Control*. Edward Arnold, London.
- Fire Research Station.** 1973. "A Standard Fire Resistance Test on a Protected Cast Iron Column." Fire No. FRO/118/034. Unpublished report on Citex Intumescent Coating.
- Gayle, Margot, David Look and John Waite.** 1980. *Metals in America's Historic Buildings: Uses and Preservation Treatments*. National Park Service, Washington, DC. A useful survey of architectural and structural use of metals, their deterioration and repair including cast and wrought iron. Extensive bibliography including period texts and periodicals. An essential reference for professionals involved in preservation projects.
- Gibbons, E.V.** 1970. *The Corrosion Behaviour of Major Architectural and Structural Metals in Canadian Atmospheres: Summary of Ten-Year Results of Group I*. Technical Paper #328. Division of Building Research. National Research Council, Ottawa.
- Gordon, J.E.** 1968. *New Science of Strong Materials*. Penguin, London.
- Greater London Council.** n.d. *Cast Iron Columns and Beams*. Materials Bulletin No. 91.
- _____. n.d. *Covent Garden - General Market Buildings*. Historical Notes: GLC Architects Dept., London. A case study of the preservation of a cast of wrought-iron framed buildings.
- Greathouse, G.A., and C. J. Wessel.** 1954. *Deterioration of Materials: Causes and Presentative Techniques*. Reinhold Publishing Corp., New York.
- Grover, H. J., S.A. Gordon and L. R. Jackson.** 1954. *Fatigue of Metals and Structures*. Department of the Navy, Washington, DC.
- Hudson, J.C.** 1940. *The Corrosion of Iron and Steel*. Chapman & Hall, Penguin, London.
- Husband, H.C.** 1975. *Reconstruction of the Britannia Bridge*. Proc. Inst. Civil Engineers, Vol. 58, Part 1, pp. 25-66.
- Insall, D.** 1972. *The Care of Old Buildings: Practical Guide*. The Architectural Press, London.

- Joint Iron Council.** 1965. *Guide to Iron Castings*. J.I.C., London.
Describes casting defect.
- Maunsell, G.A.** 1946. "Menai Bridge Re-Construction," *Journal Inst. Civil Engineers*, Vol. 25.
- Mott, Hay & Anderson.** 1923. "Report on the Condition of the Ironbridge." Unpublished report.
- National Bureau of Standards.** 1977. *Corrosion and Metal Artifacts: A Dialogue Between Conservators and Archaeologists and Corrosion Scientists*. U.S. Government Printing Office, Washington, DC.
- Pretzer, R.** 1975. *Marine Metals Manual*. International Marine Publishing Co., Camden, ME.
- Rural Industries Bureau.** 1957. *Wrought Ironwork*. RIB, London.
- Sereda, P.J.** 1974. *Weather Factors Affecting the Corrosion of Metals*. Research Paper 613. Division of Building Research. National Research Council, Ottawa.
- Waite, John G.** 1972. *Iron Architecture in New York City: The Edgar Laing Stores and The Cooper Union*. New York State Historic Trust, Albany, NY.
- Williams, J.A.** 1972. "Caring for the Ironbridge," *Ground Engineering*, Vol. 7, No. 3, pp. 36-41.

Illustrations are the property of the Heritage Conservation Program, unless otherwise noted.

VOLUME VI

CONSERVATION OF MATERIALS

4.2

METALS

CONSOLIDATION AND REPAIR

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: A. POWTER

CONTENTS

1.0 INTRODUCTION

2.0 DEFINITIONS

3.0 BIBLIOGRAPHY

1.0 INTRODUCTION

Preservation and repair of cast iron and wrought iron covers a wide field of techniques and technology. The repair of a wrought-iron hinge may require the skills of a local blacksmith while reinforcement and repair of an iron-framed bridge will require the services of consultants: engineers and architects, metallurgical consultants and highly specialized contractors.

Preservation and repair of ironwork may be required as a result of:

- a. its inability to resist superimposed loads or stresses, resulting in the failure or fracture of a structural member;
- b. damage or degradation as the result of corrosion;
- c. impact damage; and
- d. the failure of a previous repair or replacement.

The options are to repair or restore the integrity of the damaged member; to replace it with a new member of similar or substitute material; to strengthen the member by the introduction of additional material; or to clean or otherwise prepare it for protective coatings.

2.0 DEFINITIONS

Wrought iron: Literally “hammered” iron. An iron-carbon alloy containing usually 0.02 percent carbon, plus slag (iron silicate) content of about 2.5 percent. In manufacture, iron is removed from the furnace in its semi-molten state and worked with rollers or forge. Wrought iron is relatively soft, malleable, tough, fatigue resistant and easily worked by forging, bending or rolling. Currently very little wrought iron is being produced.

Cast iron: An iron-carbon alloy with high carbon content (averaging 3.0 to 4.0 percent). The use of blast air in reduction of the ore gives higher temperatures in the furnace, enabling the iron to absorb carbon from the fuel. This change lowers its melting point making it easily poured into moulds. Although there are numerous grades of cast iron with differing characteristics all cast iron is relatively brittle and rigid (withstands compressive loads). Blowholes, casting flaws, eccentricity and other unseen weaknesses can cause inconsistencies in the structural properties.

Steel: An alloy of iron and carbon containing no more than 1.7 percent carbon. Steel may include a wide variety of other elements which influence its chemical composition, heat treatments, working characteristics, and properties. Steel is classified by its carbon content.

Forging: The traditional way in which wrought-iron articles were produced. It involves cutting, heating, twisting, bending and hammering into various shapes. Parts can then be forge welded or mechanically fastened together to create the finished article.

3.0 BIBLIOGRAPHY

- Bakdvalov, G.T., and A.V. Turksouskaya.** 1965. *Corrosion and Protection of Metals*. Pergamon Press, Oxford.
- Blackwell, A.** 1976. "Notes on the Restoration of the Ironbridge." Unpublished. Salop County Council, Highways and Transport Dept.
- Burns, R.M., and W.W. Bradley.** 1967. *Protective Coatings for Metals*. Reinhold, New York.
- Chilton, J.P.** 1968. *Principles of Metallic Corrosion*. Royal Institute of Chemistry, London.
- Chong, C.V.Y.** 1977. *Properties of Materials*. Macdonald & Evans, Plymouth.
- Davey, A. et al.** 1978. *Care and Conservation of Georgian Houses*. Paul Harris Publishing with Edinburgh Newtown Conservation Committee, Edinburgh.
- Diamant, R.M.E.** 1971. *Prevention of Corrosion*. Business Books Ltd., London.
- DiGiacomo, G., J. Crisci and S. Goldspiel.** 1970. "An Ultrasonic Method for Measuring Crack Depth in Structural Weldments," *Materials Evaluation*, Vol. 27, No. 9, (September).
- Eutectic & Castolin.** *The Metal Arc Welding of Cast Iron for Maintenance and Repair Welding*. Information Sheets No. 017E, 018E, 019E, 020E, 050E, 061E. Technical Documentation Centre, London.
- Faucutt, F., and J.C. Hudson.** 1957. *Protective Painting of Structural Steel*. MacMillan, New York.
- Fire Research Station.** 1973. "A Standard Fire Resistance Test on a Protected Cast Iron Column." File No. FRO/118/034. Unpublished report on Citex Intumescent Coating.
- Gibbons, E.V.** 1970. *The Corrosion Behaviour of the Major Architectural and Structural Metals in Canadian Atmospheres: Summary of Ten-Year Results of Group I*. Technical Paper No. 328. Division of Building Research. National Research Council of Canada, Ottawa.
- Greater London Council.** n.d. *Cast Iron Columns and Beams*. Materials Bulletin No. 91.
- Greathouse, G.A., and C.J. Wessel.** 1954. *Deterioration of Materials: Causes and Preventive Techniques*. Reinhold Publishing Corporation, New York.
- Hawkes, P.W.** 1978. "Paints for Architectural Cast Iron." Unpublished. Columbia University, New York.
- Hedges, E.S.** 1932. *Protective Coatings on Metals*. Chapman & Hall Ltd., London.
- Husband, H.C.** 1975. *Reconstruction of the Britannia Bridge*. Proc. Inst. Civil Engineers, Vol. 58, Part 1, pp. 25-66.
- Inco.** 1974. "Ni-rod welding electrodes used to weld cast-iron lamp post," *Inco Echoes*, Vol. 17, No. 2.
- Insall, D.** 1972. *The Care of Old Buildings: Practical Guide*. The Architectural Press, London.
Contains a short section on cast and wrought iron as well as sporadic discussion of these metals in relation to other materials.
- Jefferson, T.B., and G. Woods.** 1967. *Metals and How to Weld Them*. 2nd edition. James F. Lincoln Arc Welding Foundation, Cleveland.
- Look, David W.** 1975. *Inventory of Metal Building Component Catalogs in the Library of Congress*. National Park Service, Washington, DC.
This bibliography covers all metals, containing 20 pages on iron, both cast and wrought. Contains many references from the period on architectural and structural uses, shop fronts, etc. Also has period references on historic preservation techniques, particularly painting and other coatings. A bit light on current preservation technology of which the most useful entries are included in this bibliography.
- Loomis, W.H.** 1901. *Twenty Five Years Experience Testing, Experimenting, and Manufacturing Protective Coverings for Iron and Steel Structural Work*. National Paint Works, Williamsport, PA.

Lowson, W.W. 1967. "The Reconstruction of the Craigellachie Bridge," *The Structural Engineer*, Vol. 45, No. 1.

Maunsell, G.A. 1946. *Menai Bridge Re-Construction*. Journal Inst. Civil Engineers, Vol. 25.

Ohlerking, R. et al. 1980. "Cast Iron," *The Old House Journal*, Vol. 8, No. 2 (Feb.), pp. 19-22.

Describes dismantling cleaning, corrosion protection and recasting with substitute materials. Short section on sandblasting contains insufficient cautions on the use of this method. Sandblasting should be used with caution and close supervision to avoid destroying the metal.

Plenderleith, H.J., and R.M. Organ. 1957. *The Conservation of Antiquities and Works of Art, Treatment, Repair, and Restoration*. Oxford University Press, London; New York; Paris.

Rudram, A.T., and L.M. Warner. 1964. "Corrosion-Inhibitive Paints," *Metallurgical Reviews*, pp. 179-200.

Scientific American. 1895. "Protection Against Rust; Gesner's Method of Protecting Iron and Steel," Vol. 72 (Apr. 27), p. 267.

Speller, F.N. 1898. *Corrosion: Causes and Prevention*. Edward Smith & Co., New York. Reprinted 1951. McGraw Hill Book Co., Inc., New York.

Waite, J.G. 1976. "Architectural Metals: Their Deterioration and Stabilization." *Preservation and Conservation: Principles and Practices*. The National Trust for Historic Preservation. The Preservation Press, Washington, DC.

Williams, J.A. 1972. "Caring for the Ironbridge," *Construction Steelwork* (October).

_____. 1974. "Remedial Work for the Ironbridge," *Ground Engineering*, Vol. 7, No. 3, pp. 36-41.

VOLUME VI

CONSERVATION OF MATERIALS

5.1

WOOD

STRUCTURE AND PROPERTIES

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: M.E. WEAVER

CONTENTS

1.0 INTRODUCTION

- 1.1 BACKGROUND
- 1.2 SCOPE

2.0 ANATOMY

- 2.1 CHEMICAL COMPOSITION
- 2.2 STRUCTURE
 - 2.2.1 *Microstructure*
 - 2.2.2 *Macrostructure*
- 2.3 GROWTH PATTERN

3.0 PHYSICAL PROPERTIES AND CHARACTERISTICS

- 3.1 APPEARANCE
- 3.2 MOISTURE CONTENT
- 3.3 DENSITY AND SPECIFIC GRAVITY
- 3.4 THERMAL PROPERTIES
- 3.5 ELECTRICAL PROPERTIES
- 3.6 DURABILITY

4.0 MECHANICAL PROPERTIES

- 4.1 AXIAL, BENDING AND SHEAR STRENGTH
- 4.2 STIFFNESS
- 4.3 TOUGHNESS
- 4.4 HARDNESS
- 4.5 EFFECTS OF AGING

5.0 BIBLIOGRAPHY

1.0 INTRODUCTION

This article describes the structure of wood (including its formation and chemical composition) and identifies those properties and characteristics that influence the selection, evaluation, treatment and preservation of wood in historic structures.

1.1 BACKGROUND

Conservators are often faced with the task of assessing and treating historic wooden elements in varying states of deterioration. Wood, being an organic material, is susceptible to change and decay through the natural process of aging and the effects of unfavourable environmental conditions. A basic understanding of its composition and properties is essential for the judicious selection of suitable restoration measures.



Mt. Currie, BC

Photograph courtesy of the Canadian Inventory of Historic Building

1.2 SCOPE

This article is intended for use by professional and technical personnel who direct or conduct analytical investigations of historic structures. It briefly describes the anatomy of wood and the physical and mechanical properties that distinguish it as a building material. No attempt is made to tabulate specific data for the different species found in Canada. This information is readily available in standard texts and handbooks such as those listed in the bibliography.

2.0 ANATOMY

2.1 CHEMICAL COMPOSITION

The properties of wood are dependent not only on its cellular structure, but also on the nature and organization of the chemical compounds which make up the cells.

Wood tissue is comprised of holocellulose (60 to 80 percent), lignin (15 to 35 percent), secondary components such as tannins, resins (2 to 10 percent) and water.

Holocellulose is divisible into insoluble cellulose and alkali-soluble hemicellulose. The former is the major component both in terms of volume (40 to 50 percent) and its effect on the characteristics of wood. A carbohydrate, it can be described as a stable, fibrous residue of woody tissue, very resistant to attack from many common acids, bases and solvents. Hemicellulose is different in that it contains more than one kind of sugar in its molecular makeup. It does not build up fibres but is glutinous in nature. In combination, these two celluloses impart strength to the cell wall.

Lignin, the other major component of wood, is an inert, insoluble polymer. Its most important property is its rigidity, imparting stiffness to the cell walls.

2.2 STRUCTURE

There are two general classifications for wood:

- softwood – from coniferous trees bearing needles
- hardwood – from broad-leaved trees.

2.2.1 Microstructure

As with all living tissue, wood is comprised of individual units called cells. They differ in size, shape and properties depending on their required function and the type of tree. It is the makeup of these cells that give the different species of wood their characteristics.

The basic cellular units are described and sketched below.





TYPICAL CELLULAR STRUCTURE OF WOOD

cell function	class of tree	
	softwood	hardwood
sap conduction	thin-walled tracheids	vessels
support	thick-walled tracheids	fibres
storage and horiz. conduction of food	parenchyma	parenchyma

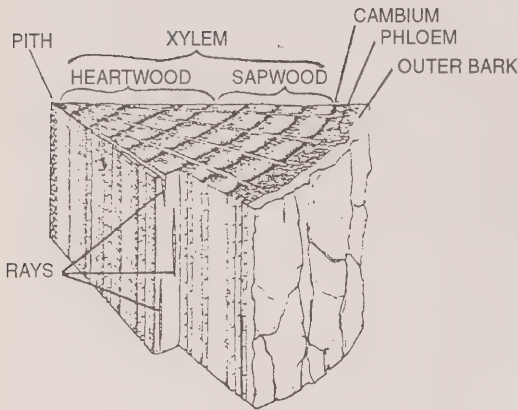
One common feature of all these cells is the presence of valve-like pits in the cellular walls. Although there are different types of pits, they all serve a common function – to control the movement of liquids between the cells. These pits give each species of wood its characteristic permeability, a property which controls its ability to intake liquid wood preservative and its tendency to become waterlogged.

Cell contents such as deposits of silica may often be the food of certain insects or fungi.

TYPES OF CELLS

TYPE	DESCRIPTION	APPEARANCE
tracheids	Long (approximately 3 mm) tubular cells with many valv pits in their walls to control the flow of sap. Walls are thick or thin depending on function.	
vessels	short, open-ended, pipe-like cells with wall pits.	
fibres	short, thick-walled needle shaped cells.	
parenchyma	Small thin-walled, box-like cells. Generally arranged in horizontal bands or rays which run across grain in a radial pattern.	

Types of Cells



Major Elements of Wood Structure

2.2.2 Macrostructure

Regardless of whether a tree is classed as a softwood or hardwood, its transverse anatomical structure is made up of five principal concentric layers, each with its own function and properties:

a. Pith:

Located at the heart of the trunk and containing only cellular material, the pith is the first part of the stem formed. As the tree grows, the pith's moisture or sap distribution function is taken over by the xylem layers. No longer in use, this core dries up and is susceptible to decay.

b. Xylem :

The xylem constitutes the major portion of the central core of a mature tree and along with the pith, is commonly considered to be the 'wood' of the trunk. It is actually divisible into two more discrete layers – the outer and youngest being sapwood, the inner, heartwood. Sapwood is the most recently formed wood and both conducts fluid and stores food. It is through this living layer that sap, water and dissolved minerals flow up the tree. Unfortunately, due to its characteristic permeability, sapwood is susceptible to decay.

The heartwood differs from the sapwood in that it no longer carries sap. As the wood cells progressively become removed from the active growth region (cambium),

they die and undergo a slow chemical change. The wood becomes stronger, harder and darker in colour. This change also makes the heartwood more resistant to fungal and insect attacks because of the presence of extractions that are toxic to some wood-deteriorating organisms. Although the cells are dead, the heartwood gives the tree its strength and rigidity. As long as this layer is sealed off from the air by living tissue on the outside, it remains strong. However, if it is exposed to air, decay can commence and the tree may become hollow and lose its rigidity.

c. Cambium:

A tree grows in diameter as the result of repeated divisions of cambial cells. This produces wood cells on the inner xylem face and phloem cells on the outer. This specialized layer is only one cell thick.

d. Phloem or inner bark:

The phloem supplies nutrients to the tree. This layer, a narrow zone of thin-walled active cells, is generally removed with the outer bark when the tree is converted into timber.

e. Outer bark:

This exterior layer protects the tree from the effects of sudden changes or extremes of temperature, from moisture loss, against fungal and insect attack and mechanical injury.

2.3 GROWTH PATTERN

If a cross section of a tree trunk is examined, one will notice a number of concentric rings in the xylem. These are growth or annual rings and reflect the life history of the tree recorded in the structure of the wood. Each growth layer consists of the wood produced by the cambium in a single growing season.

3.0 PHYSICAL PROPERTIES AND CHARACTERISTICS

3.1 APPEARANCE

The distinguishing characteristics of wood described below differentiate various species and often promote the preferential use of wood.

- a. Grain refers to the direction of fibre alignment relative to the longitudinal axis of the trunk. Six types of grain may be distinguished: straight, cross, diagonal,

spiral, interlocked and wavy. The slope of the fibres influences both the timber strength and appearance.

- b. Texture describes the relative size and the amount of variation in size of wood cells. Softwoods are generally fine textured since the tracheids, which make up the majority of their cellular structure, have relatively small diameters. Hardwoods, which have large vessels and broad rays, are classed as coarse textured. In addition, the alternation of the zones of springwood and summerwood also influences texture: when the contrast between the zones is strongly marked, the wood is said to be unevenly textured and when there is little or no contrast the wood is said to be evenly textured.
- c. Figure is any design or distinctive markings derived from irregular grain patterns, colour, growth rings and the distribution of certain types of tissue. Common types of figure are distinguished as birdseye, burl, fiddleback or wavy, ribbon or strip.
- d. Colour, for identification purposes, generally refers to that of the heartwood since the sapwood is paler and seldom distinctive. Abnormal colourations are usually indicative of incipient decay caused by fungal organisms.
- e. Lustre is the property that enables wood to reflect light. Useful only as a secondary identification feature, the loss of lustre is one evidence of incipient decay.

3.2 MOISTURE CONTENT

Moisture content is the weight of water in wood, expressed as a percentage of its oven-dry weight. The moisture content and change of moisture content of wood affects its behaviour in several critical ways. Besides strength and dimensional stability, which are discussed below, the moisture content and change of moisture content of wood have a direct influence on the density of the specimen and its susceptibility to attack by some insects and by fungi that cause stain or decay.

- a. Effect on dimensional stability:

As the moisture content increases, wood swells; as it decreases, wood shrinks. Dimensional changes are not, however, the same in all directions. Movement in the longitudinal direction is between one percent and two percent of that for the transverse direction. Due to its relative insignificance, longitudinal movement is gener-

ally disregarded. The same cannot be said for the transverse movement which can be up to a maximum of 14 percent in the tangential direction and seven percent in the radial direction. This uniform shrinkage can cause a detrimental degree of distortion in the form of bowing or cupping as a piece of green timber seasons.

- b. Effect on strength:

As the moisture content decreases below the fibre saturation point (point where all water is evaporated from the cell cavities but the cell walls are still fully saturated with moisture), most strength factors increase almost linearly. The only detrimental effect is a slight decrease in toughness. Seasoning defects may develop, offsetting any increase in strength properties as the timber dries. Once a specimen has dried beyond a given moisture content, fluctuations in moisture content tend to lower the strength properties and increase the brittleness of the wood.

3.3 DENSITY AND SPECIFIC GRAVITY

The density of wood reflects the amount of cell-wall substance relative to air spaces within the wood structure. Fluctuating both with species and moisture content (green wood weighing significantly more than its seasoned counterpart), the range of wood-density values lies between 80 and 1120 kg/m³.

Wood may be roughly grouped into five classes according to density:

Class	Density kg/m ³
very light	less than 240
light	241 to 560
medium	561 to 720
heavy	721 to 960
very heavy	greater than 960

The density provides a reliable guide to the strength of timber. The specific gravity of a wood can also be directly related to its strength properties.

3.4 THERMAL PROPERTIES

The thermal conductivity of wood is directly proportional to the density and moisture content of the timber. For this reason, low density woods, such as balsa, make excellent insulators.

The coefficient of thermal expansion in the longitudinal direction is approximately 3.4×10^{-6} per degree Celsius regard-

less of species or specific gravity. It is about ten times greater in the transverse direction. However, dimensional changes due to thermal expansion and contraction are not normally a problem because wood is usually used within a narrow range of temperatures and because changes in dimension caused by moisture fluctuations usually cancel these effects.

The ignition temperature of wood is approximately 273°C

3.5 ELECTRICAL PROPERTIES

Wood possesses electrical resistance which decreases as the moisture content and temperature increase.

This relationship is the basis of the function of moisture meters.

3.6 DURABILITY

The durability of wood refers to its ability to resist attack by foreign organisms, particularly fungi, insects and marine borers. The term most frequently means natural resistance to decay (attack) by wood-destroying fungi. Sapwood is less durable than heartwood because it lacks extractives, the extraneous materials such as oils, tannins and phenolic substances present in heartwood, which are toxic to wood-inhabiting fungi and hence act as natural preservatives. The durability of wood is affected by density, growth rate, climate and state (living or dead).

Classes of durability include:

Grade of natural durability	Approximate stake life in contact with ground (years)
very durable	greater than 25
durable	15 to 25
moderately durable	10 to 15
non-durable	5 to 10
perishable	less than 5

4.0 MECHANICAL PROPERTIES

The mechanical or strength properties of wood measure its overall condition and ability to resist applied or external forces. These properties largely determine the suitability of various wood species for structural or building purposes. There are

few uses for wood that do not depend on one or more of its strength properties.

Values for static strength properties of common species of wood at varying levels of moisture content can be found in the texts listed in the bibliography.

4.1 AXIAL, BENDING AND SHEAR STRENGTH

Mechanical properties which govern the use of wood as a major construction material are strengths in compression, tension, bending and shear. Because of the anisotropic nature of the material, these strengths vary depending on whether the stress is applied parallel to (along) or perpendicular to (across) the grain. The magnitude of the load required to cause failure in bending is expressed by the modulus of rupture.

As discussed previously, timber strength is affected by density, moisture content and growth features such as slope of the grain and knots.

4.2 STIFFNESS

Stiffness is a measure of resistance to deformation generally expressed in terms of the modulus of elasticity. As the modulus increases, the resistance increases. True to its anisotropic nature, there are three moduli dependent on the direction; the tangential and radial values being between 1/20 and 1/12 of their longitudinal counterpart. As with other properties, the actual value depends not only on the species of tree but also its moisture content. In general, softwoods rank higher in stiffness than hardwoods of the same approximate density.

4.3 TOUGHNESS

Toughness is the capacity of a piece of wood to undergo deformation beyond the proportional limit (point beyond which linear relationship between load and deformation ceases) before complete failure. Samples which bend a great deal and break gradually with the absorption of much energy can be described as tough as opposed to brittle.

4.4 HARDNESS

Hardness is a measure of the wood's resistance to indentation. It is primarily dependent on the amount of cell wall present.

4.5 EFFECTS OF AGING

Only a limited amount of data is available for the effects of aging on the mechanical properties of wood. Initial research had indicated that, in comparing aged timbers with new timbers at the standard moisture content of 12 percent, the modulus of elasticity is slightly lower; the modulus of rupture is slightly higher, and the compressive strength perpendicular to the grain is considerably lower.

The latest available experimental data, however, concludes that the mechanical properties of wood are not affected by age and that, in design, the allowable mechanical properties of new wood can be used, considering the physical condition of the aged timber and its environment. These contradictory results only reinforce the need for more research in this area.

5.0 BIBLIOGRAPHY

- Attar-Hassan, G.** 1976. "The Effect of Aging on the Mechanical Properties of Eastern White Pine," *Bulletin of the Association for Preservation Technology*, Vol. 8, No. 3, Ottawa.
- Bramwell, M.** 1976. *International Book of Wood*. Simon & Schuster, New York.
- Canadian Wood Council.** 1977. *CWC Datafile For Wood Design & Construction, SP-1: Structure and Properties*. Ottawa.
- Crysler, R.E.** 1978. *Mechanical Properties of Some Aged Timbers*. Report on file with Restoration Services Division. Department of Indian and Northern Affairs, Ottawa.
- Desch, H.E.** 1973. *Timber: Its Structure and Properties*. 5th edition. St. Martin's Press, New York.
- Edlin, H.L.** 1969. *What Wood Is That? A Manual of Wood Identification*. Thames and Hudson, London.
- Findlay, W.P.K.** 1975. *Timber: Its Properties and Uses*. Crosby Lockwood Staples, London.
- Indian Affairs and Northern Development, Dept. of.** 1979. *Preserving Historic Structures in Canada: Wood: A Study Guide and Source List*. Report No. EA-HQ-79-42. Architecture and Engineering Services, Ottawa.
- Kollman, F.F.P., and W.A. Côté.** 1968. *Principles of Wood Science and Technology, Volume I: Solid Wood*. Springer-Verlag, New York.
- Lampkin, K.P.** 1980. *Mechanical Properties of Aged Timber*. 4th year project, Department of Civil Engineering, Carleton University, Ottawa.
- Longman Group Ltd.** 1973. *Materials & Technology: Volume VI, Wood, Paper, Textiles, Plastics & Photographic Materials*. London.
- Panshin, A.J., and C. de Zeeuw.** 1970. *Textbook of Wood Technology, Volume I: Structure, Identification, Uses and Properties of the Commercial Woods of the United States and Canada*. 3rd edition. McGraw Hill, New York.
- Rendle, B.J.** 1969. *World Timbers, Volume 2: North and South America*. Ernst Benn Ltd., London.
- Resources and Development, Dept. of.** 1951. *Canadian Woods: Their Properties and Uses*. Forest Products Laboratory Division, Forestry Branch, Ottawa.
- Silverter, F.D.** 1967. *Mechanical Properties of Timber*. Pergamon Press, Oxford.
- United Kingdom.** 1972. *Handbook of Hardwoods*. Building Research Establishment, Department of the Environment, London.
- . 1977. *A Handbook of Softwoods*. Building Research Establishment, London.
- U.S. Dept. of Agriculture.** 1974. *Wood Handbook: Wood as an Engineering Material*. Forest Products Laboratory, Forest Service, Washington, DC.
- . n.d. *American Wood Series*. Forest Products Laboratory, Forest Service, Washington, DC.
- Wangaard, F.** 1950. *The Mechanical Properties of Wood*. John Wiley & Sons Inc., New York.
- Weaver, M.E.** 1978. *Preserving Historic Structures in Canada: Wood*. Unpublished ms. Department of Indian Affairs and Northern Development, Ottawa.
- Western Wood Products Association.** 1973. *Western Woods Use Book: Structural Data & Design Tables*. Portland, OR.

Illustrations are the property of the Heritage Conservation Program, unless otherwise noted.

VOLUME VI

CONSERVATION OF MATERIALS

5.2

WOOD

GROWTH, CONVERSION AND SEASONING DEFECTS

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: M.E. WEAVER

CONTENTS

1.0 INTRODUCTION

2.0 GROWTH-RELATED DEFECTS

- 2.1 CROSS-GRAIN
- 2.2 KNOTS
- 2.3 PITCH POCKET OR BARK POCKET
- 2.4 FROST RIBS
- 2.5 CHECKS AND SHAKES
- 2.6 COMPRESSION WOOD AND TENSION WOOD

3.0 CONVERSION AND RELATED DEFECTS

- 3.1 TREE MATURITY
- 3.2 AGING
- 3.3 SAWING

4.0 SEASONING AND RELATED DEFECTS

- 4.1 MOISTURE CONTENT
- 4.2 DRYING
- 4.3 SHRINKAGE
- 4.4 TEMPERATURE
- 4.5 CASEHARDENING

5.0 RECOMMENDATIONS

6.0 ACKNOWLEDGEMENTS

7.0 BIBLIOGRAPHY

1.0 INTRODUCTION

Recognizing potential defects related to the growth, conversion and seasoning of wood is helpful in establishing appropriate treatment and maintenance procedures for historic buildings.

Since modern methods of converting logs to structural timbers or planks differ from traditional methods, potential faults or discrepancies should be recognized before new wood is used in restoration.

The following deals with wood and timber used for the construction and finishing of buildings and is limited principally to soft woods.

2.0 GROWTH-RELATED DEFECTS

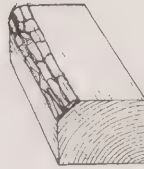
During the growth of a tree, faults may develop which later affect the strength and utility of cut timber. First, the natural growth patterns of the tree may produce variations in form. Second, external forces can cause damage to a tree and influence its growth. Trees very rarely, if ever, grow perfectly straight and cylindrical without some local imperfections.

2.1 CROSS-GRAIN

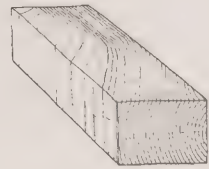
One of the most common growth-related defects in wood is cross-grain. Cross-grain describes a condition where the grain of the wood is not parallel to the trunk and crosses the timber diagonally.

Change in grain direction can weaken the timber by causing cross-grain loading. As a result, the load will not be carried consistently and the wood may fail because of overstressing at a particular point.

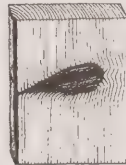
Cross-grain may be caused by the natural spiral growth tendencies of some species, by peculiar individual formation or by major grain disturbances around knots or previously injured areas of the trunk. Cross-grain should be distinguished from "diagonal grain," which is the result of sawing parallel to the pith rather than parallel to the bark of tapered trunks or logs. The effect may be similar, but diagonal grain is not related to the actual growth pattern of the tree.



WANE



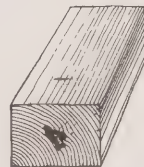
CROSS GRAIN UPSETS



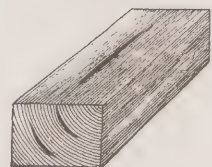
SPIKE KNOT



LOOSE KNOT



BARK POCKET



RESIN POCKETS

Growth Related Defects in Wood Showing Natural Intrusions in Sawn Timber

2.2 KNOTS

A second characteristic of the growth pattern of wood which may affect its performance is the frequency and size of knots. Knots interrupt the direction of growth, causing localized cross-grain and modifying the properties of a section.

Because of the continuity of wood fibres around a knot, most knots do not affect the strength of a structural member. Occasionally a loose knot or a spike knot – the remains of a broken branch – may occur at a point of stress. This defect is easily seen and may occasionally be found in historic structures. This condition should be avoided in reconstruction or repair.

2.3 PITCH POCKET OR BARK POCKET

In conifers, damage to the bark, cambium (inner bark) and immature xylem (growth layer) can result in an excessive concentration of resin at the point of the wound. When growth continues, the concentration of resin or pitch can be overgrown and the result is a pitch pocket. Bark may also be included in the wood at the point of damage. This phenomenon is known as a bark pocket.

2.4 FROST RIBS

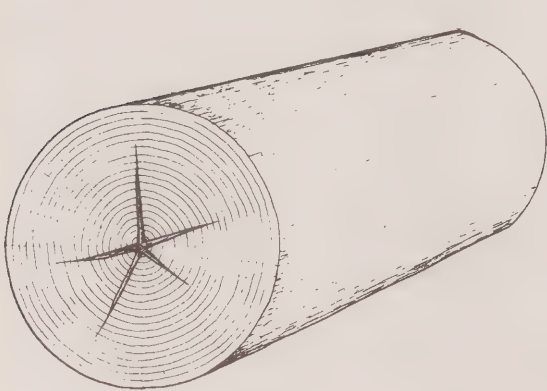
Frost and low temperature can result in two types of injury to the growing tree. First, a false ring of weak discoloured cambium and xylem cells may be formed, resulting in a potential line of failure. Second, a crack may develop in the bark, cambium or xylem. This crack may be bridged in subsequent seasons by new cambial growth, but the bridging tissue

will be weak in tension. Repeated failing and healing will eventually build up a formation of protruding lips of callus which are known as frost ribs.

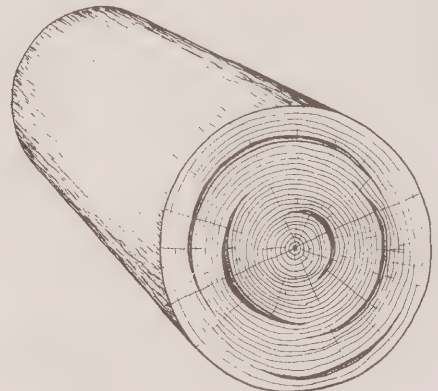
2.5 CHECKS AND SHAKES

Checks and shakes are longitudinal separations in the wood which develop in the standing tree. A simple heart check is a crack running through the pith outwards from the heart of the tree. Heart checks develop when the tensile strength perpendicular to the rays is lower than tensile growth stresses. If a number of cracks radiate outwards in this manner the result is called a star check.

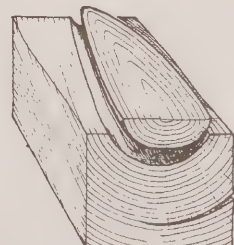
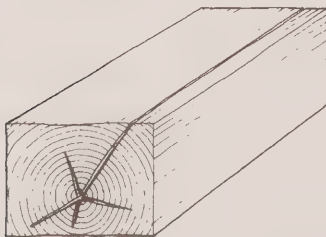
Ring shakes or round shakes are separations of the wood following the growth rings. They are the results of failures of weak tissue under various types of load.



HEART CHECKS



SHAKES



Growth Related Defects Showing Separation of Fibres

2.6 COMPRESSION WOOD AND TENSION WOOD

Compression wood is an abnormally dense wood formed on the lower side of heavy branches or of leaning trunks. Normally found in softwoods (conifers), compression wood shrinks excessively in length when dried. Timbers which include compression wood can therefore bow, twist and crook.

In cross-section, compression wood looks like heavy summer wood, often with eccentric, relatively wide growth rings. In a historic structure, what appears to be deflection under load may actually be the result of the shrinking or bowing of timbers which include compression wood.

Tension wood is normally found in hardwoods on the upper side of heavy branches or leaning trunks. Its behaviour also differs from that of normal wood. It tends to shrink excessively along the grain and machining tension wood can lift fibres in bundles and make the surface woolly. This woolly surface is known as fuzzy grain because of the hairy appearance of the damaged cells or fibres.

3.0 CONVERSION AND RELATED DEFECTS

Conversion is the term used to describe the process of obtaining usable pieces of wood from a tree.

3.1 TREE MATURITY

To provide wood for construction and finishing purposes, trees should be felled at "maturity." If a tree is felled too young it will contain a high proportion of sapwood and the quality of the final product will not be strong or durable. If the tree is too old, growth will have slowed down and although there will be a large quantity of heartwood, it will be brittle and inelastic. The age of maturity varies from species to species. Oak, for example, is considered mature at 100 years, ash, elm and larch at 50 years and poplar at 30 years.

3.2 AGING

When the tree is felled, it is stripped of its bark and cambium to facilitate drying. The log is then immediately cut lengthwise to approximately the dimensions required. As the log ages, checks or cracks may occur but normally these do not appreciably affect strength.

Traditionally, it is said that logs were submerged in water to age; however, the floating of logs should not be considered a seasoning procedure. Water protects the log from fungal attack, providing the log is completely submerged. Aging in water will not prevent stain and decay in any portion of the log exposed to air.

3.3 SAWING

In the past, quality lumber was "rift sawn." The resultant board was termed "quarter-sawn." In quarter-sawn lumber, the growth rings pass almost straight across the section perpendicular to the face, making the lumber more consistent in pattern, harder-wearing and more stable.

Today most trees are sawn for maximum recuperation without regard to stability. The common type of conversion, tangential sawing, produces many "plain-sawn" or tangential sections. These are more prone to warping and distortion due to the different shrinkage rates of the exposed faces.

4.0 SEASONING AND RELATED DEFECTS

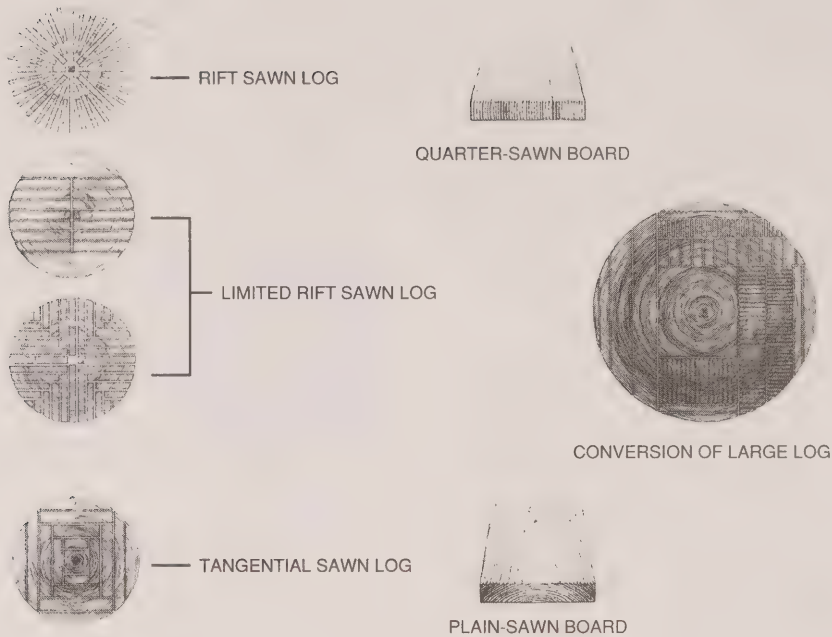
Seasoning is the process of drying timber to a moisture content appropriate to its intended use.

4.1 MOISTURE CONTENT

A growing tree may contain as much as 150 to 200 percent water relative to its oven-dry weight. As soon as the tree is felled, it starts to lose water from the cavities of the cells. This is termed free moisture. Normally no dimensional changes accompany this loss. Wood which has lost all the free moisture from the cell cavities is described as being at "fibre saturation point." Fibre saturation point normally occurs when the moisture content reaches 25 to 30 percent of the oven-dry weight of the wood.

4.2 DRYING

As wood gives up moisture, there is a greater drying effect on the outside and ends of the timber than in the interior. Hence, the external surface zone is liable to contract faster than the interior. This difference in shrinkage rates can cause surface and end checks. If the relative humidity of the atmosphere around the timber is too low during the initial stages of drying, the end or surface checking will be excessive.



Conversion is the term used to describe the process of deriving usable pieces of wood from a tree. The quality of lumber produced is affected by the method of conversion employed: higher quality usually involves more complex cuts, consequently more time and more cost.

4.3 SHRINKAGE

If wood continues to dry below the fibre saturation point, the shrinkage will not be equal in all directions. Shrinkage along the grain is negligible except in reaction wood and in spiral or cross-grained timbers. But shrinkage across the grains is considerable and about twice as much shrinkage occurs in the tangential direction as in the radial direction.

When differing rates of shrinkage occur simultaneously in two or three directions, the resultant stresses can lead to breaks in the wood tissue. Plain sawn boards will also warp excessively with changes of moisture content in the wood.

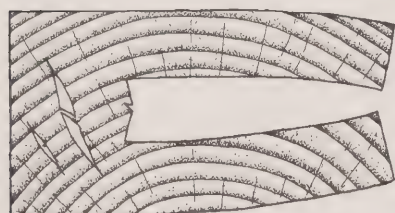
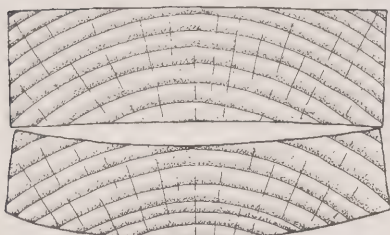
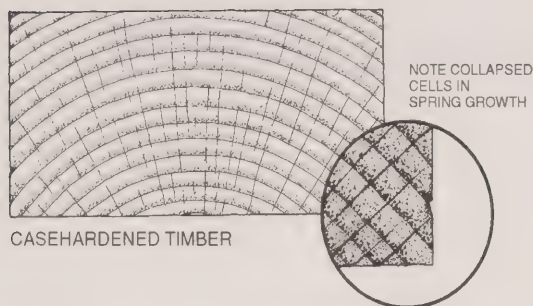
4.4 TEMPERATURE

Temperature is important in the drying process because it affects the rate at which moisture moves from zones of high

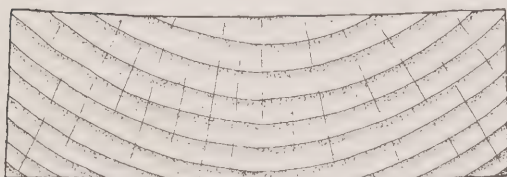
moisture content to zones of lower moisture content. If the temperature is too high, collapse can occur. This defect develops during the initial stages of drying when cells are filled with water. If drying is too rapid, the tensile stresses in the core can be sufficient to cause honeycombing as the cells retract from one another, leaving spaces between.

4.5 CASEHARDENING

Casehardening is a defect associated more with modern kiln-drying techniques than with historic air-drying. If a timber is dried too fast, the outer layers may set on the undried core. If no checking occurs as the core dries, the core will be placed in tension with the outer shell in compression. With unrelieved stresses in the wood, serious checking will develop and collapse or honeycombing may result.



*Casehardened wood may be stable until cut;
following a cut it will warp or cup*



Warping in a plain sawn board will occur with a reduction in moisture content.

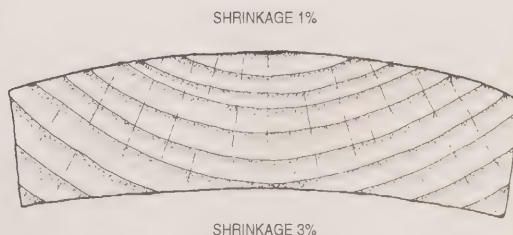
5.0 RECOMMENDATIONS

In conclusion, it is recommended that wood used in the restoration of historic structures be chosen, converted and seasoned in the manner most closely resembling the original. It is also recommended that a moisture content similar to the existing structure be achieved before new wood is incorporated in the work. In this way it is possible to predict that the behaviour of new wood will conform most closely to the structure with which it is being matched and that a minimum of dislocation will occur as the wood continues to age.

To achieve this to the greatest degree of accuracy possible, it is important that moisture content, methods of conversion and the degree to which natural faults may be required or tolerated in replacement wood be assessed and then specified in contract documents.

6.0 ACKNOWLEDGEMENTS

Drawings: Lise Potvin



20% MOISTURE CONTENT

7.0 BIBLIOGRAPHY

Canadian Wood Council. *Structure and Properties of Wood.* Canadian Wood Construction Series. Ottawa.

Department of Resources and Development. 1961. *Canadian Woods: Their Properties and Uses.* Forest Products Laboratories Division, Forestry Branch. Department of Resources and Development, Ottawa.

Desch, H.E. 1973. *Timber, Its Structure and Properties.* 5th edition. London.

Eades, H.W. 1932. *British Columbia Softwoods: Their Decays and Natural Defects.* Department of the Interior, Ottawa.

Hosie, R.C. 1973. *Native Trees of Canada.* 7th edition. Environment Canada, Ottawa.

MacMillen, J.M. 1956. *Stresses in Wood During Drying.* Forest Products Laboratory Report 1652. U.S. Department of Agriculture, Madison.

U.S. Department of Agriculture. 1974. *Wood Handbook: Wood as an Engineering Material.* U.S. Forest Products Laboratory, Agriculture Handbook 72. Washington, DC.

Illustrations are the property of the Heritage Conservation Program, unless otherwise noted.

VOLUME VI

CONSERVATION OF MATERIALS

5.3

WOOD

WEATHERING AND AGING

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: M.E. WEAVER

CONTENTS

1.0 INTRODUCTION

2.0 HUMIDITY

3.0 TEMPERATURE

4.0 ABRASION

5.0 ANIMALS

1.0 INTRODUCTION

This article describes some of the potential effects of weathering and aging on wood in historic structures. Understanding these effects is important when designing and carrying out maintenance and restoration programs and when introducing new material into the historic environment.

2.0 HUMIDITY

All problems of seasoning can occur again and again in-situ and with extreme variations of humidity, physical degradation of the wood can result.

It is quite possible for a timber to take up sufficient moisture from its environment to expand to its original “green” dimensions. The resultant swelling of the wood can break the structure or assembly.

When a piece of wood takes on moisture and then loses it again, the external surfaces will tend to dry faster than the interior. In some timbers (e.g. boards), the wood on one face may be fast-drying sapwood while the other may be slower-drying heartwood. Such timbers will be prone to warping or cupping. Checking and honeycombing can also result from extremes of differential expansion and contraction in moisture cycling conditions. Drying can cause warping, splitting and checking where differential stresses occur.

Tangentially sawn floorboards, which are repeatedly wetted and dried, tend to suffer from a more localized form of deterioration which produces raised grain. Splinters can develop because of the very different shrinkage and swelling rates of springwood and summerwood.

At its most severe, repeated wetting and drying, with associated expansion and contraction, can lead to a complete disruption of the fibres and an accompanying chemical decomposition. This is sometimes known as “damp rot,” a misleading title since this is not a rot or biological attack, although it may superficially resemble one.

3.0 TEMPERATURE

If a timber in a building has been continuously subjected to high temperatures, its organic components can break down to carbon dioxide and water (see Section 5.6 “Wood: Damage

by Heat and Fire”). Hemicellulose is the most prone to this phenomenon of thermal degradation, followed by cellulose and to a lesser degree, lignin.

Thermal degradation causes a loss of weight. Initially there is little change in the modulus of rupture, but very considerable losses of abrasion resistance and toughness occur.

The severity of the degradation is not only dependent upon temperature and exposure time, but also on the presence of moisture. The latter makes the effects much more severe. At a steady exposure to a temperature of 20°C, the wood will lose about one percent of its weight in 100 years and 10 percent in 1000 years. Plotted on a graph, the constant weight loss would practically be a straight line.

Deterioration by thermal degradation of wood in service is most commonly observed when the wood is abraded. Whole masses of fibres fall away because the fibre-to-fibre bond has been lessened by the thermal severing of the hemicellulose chains.

4.0 ABRASION

Repeated abrasion can also cause fibre disruption and a steady removal of minute amounts of the exposed wood surface.

For example, exposure to blown sand or dust will eventually wear a timber completely away.

“Human erosion” at historic sites with high visitation rates is also a particularly difficult and similar problem. When many thousands, perhaps millions, of feet pass across a wooden door sill, each shoe grinds a little gritty dirt beneath it. The final result is the same as sandpapering. Passing vehicular traffic can also cause physical damage. Many medieval timber buildings which front on narrow streets in England, have, in recent years, been continually struck or scraped by passing trucks. High projecting timbers, such as those found in overhanging jetties, are particularly prone to this form of damage.

5.0 ANIMALS

Animals, especially rodents, may chew timber or abrade it in other ways. Farm buildings are particularly prone to this type of damage and timber in this context may be damaged in a large number of ways, ranging from “crib biting” or “crib-bing” to gnawing by rats.

VOLUME VI

CONSERVATION OF MATERIALS

5.4

WOOD

FUNGAL DECAY AND STAINING

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: J.K. SHIELDS AND M.E. WEAVER

CONTENTS

1.0 INTRODUCTION

2.0 GROWTH AND REPRODUCTION OF FUNGI

3.0 CONDITIONS FOR GROWTH

3.1 AIR

3.2 MOISTURE

3.3 TEMPERATURE

4.0 TYPES OF FUNGI

4.1 MOULDS AND SAPSTAIN FUNGI

4.2 WOOD-DESTROYING FUNGI

4.2.1 *Brown Pocket Rot – Lenzites trabea, Pers.
and L. Saepiaria, Fr*

4.2.2 *Dry Rot – Merulius Lacrymans, (Wulf) Fr.
and Poria Incrassata (B. and C.) Curt*

5.0 TREATMENT OF FUNGI

6.0 APPENDIX: IDENTIFICATION OF FUNGI

7.0 BIBLIOGRAPHY

1.0 INTRODUCTION

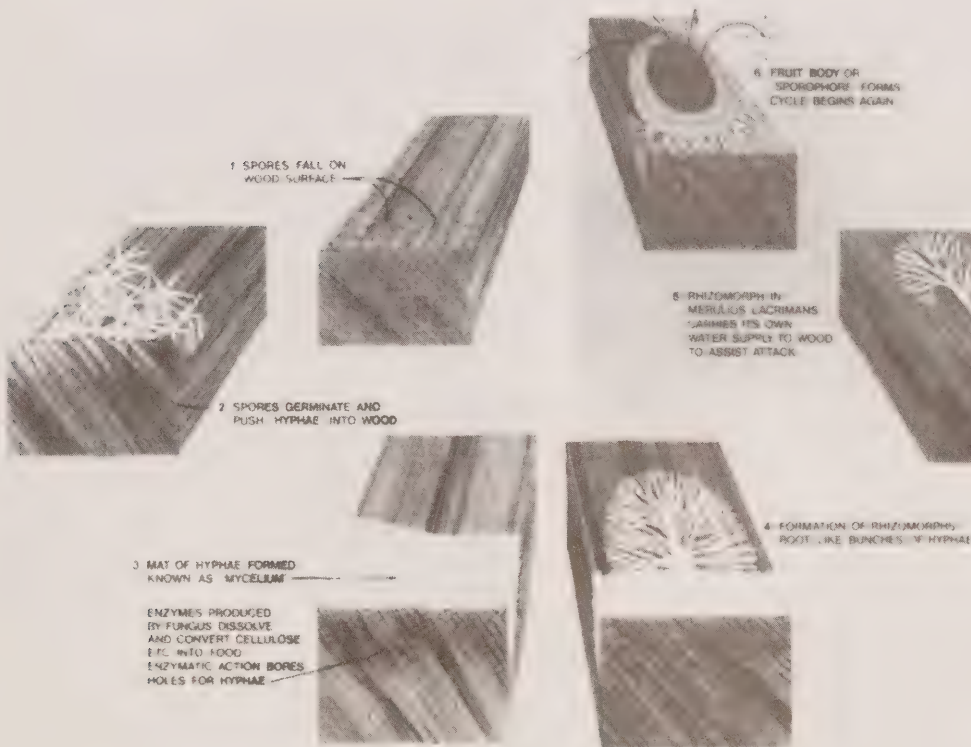
The preservation of wood in historic structures involves a continuing fight against deterioration. One of the principal sources of wood deterioration is fungal decay. Given optimum conditions of temperature, humidity and air, fungi can destroy the integrity of a wood structure in as little as one or two years.

This article describes the principal characteristics and effects of the major wood-staining and wood-destroying fungi found in Canada.

2.0 GROWTH AND REPRODUCTION OF FUNGI

Fungi are composed of tube-like conductive tissue, called hyphae or mycelium, which secrete enzymes. These enzymes enable fungi to digest the cell walls of wood and their contents, destroying their consistency.

Reproductive structures (fruiting bodies or sporophores) may be produced from the hyphae and are used to identify the many thousands of fungal species.



Growth and Reproduction of Fungi

At maturity, fungi produce millions of seed-like bodies called spores. These spores may travel long distances in air or water droplets or may be carried by insects feeding upon the mycelium or strophophores. Spores which reach moist wood can germinate and develop new areas of decay.

Fungal damage may also spread from decayed material to sound uninfected wood when hyphal strands develop between them, provided moisture conditions are suitable.

3.0 CONDITIONS FOR GROWTH

The development and spread of wood-inhabiting fungi requires food supplied by wood components such as cellulose, lignin and cell contents. While certain woods are more susceptible to attack, all species will eventually be destroyed by fungi if suitable conditions of air, moisture and temperature are provided.

3.1 AIR

The air supply contained in wood cells of forest products is usually adequate to support fungal growth. If air is removed, as in saturated wood (submerged logs) or is contaminated by the introduction of toxic gases (fumigation), decay will be arrested. Arrest can also take place in conditions where wood is exposed to decay in a sealed enclosure. The available air is replaced by carbon dioxide, one of the major products of the breakdown of wood by fungi.

3.2 MOISTURE

Moisture is most important in affecting the development of fungi. Moisture in combination with air can govern the extent of decay.

The infection of wood, through the germination of spores or penetration of mycelium, requires both a moist surface and a humid environment. Once the fungus is below the surface of the bark, a balance of air and water is required to maintain the decomposition of cellular material.

Wood is considered immune to decay if it is kept below 20 percent moisture content, but fungi which may be present in the wood will not necessarily be killed under these conditions. Certain species can remain dormant for long periods and can revive, continuing the decay process, if the wood becomes sufficiently wetted.

3.3 TEMPERATURE

Fungi, like other plants, grow more rapidly in warm weather. The optimum temperature for many wood destroyers is around 27°C. Fungi become dormant under freezing conditions. Although there is a small group of fungi (thermophiles) which is active above 35°C, most species are killed by prolonged exposure to temperatures above the maximum for growth. Conditions in commercial drying kilns, where temperatures above 65°C are used, completely sterilize wood.

4.0 TYPES OF FUNGI

Wood-inhabiting fungi can be classified broadly in two types depending upon their capacity to break down and digest the lignin and cellulose in cell walls. These two groups are a) moulds and sapstain fungi and b) wood-destroying fungi.

4.1 MOULDS AND SAPSTAIN FUNGI

Moulds and sapstains cause little or no damage to structural elements and do not reduce strength of wood significantly. They are undesirable because they cause unsightly discolorations – shade of black-blue, green, yellow and pink.

While not important in themselves as agents of decay, moulds are significant because they act as warning signs that conditions are favourable for fungal growth and a more serious attack by a true wood-destroyer.

The growth of moulds is largely superficial and often they can be removed by brushing or planing the wood. (Historic wood, in most cases, should not be planed to remove moulds.)

Sapstains are important mainly for their unsightly effect. True sapstaining fungi do not decompose the wood substance proper but derive nourishment from food materials stored in the cells of sapwood. Some sapstains will develop inside a piece of timber and show no sign of staining on the outside. This occurs if outer layers are too dry for fungal growth while inner layers are still sufficiently wet to support growth. Some moulds and sapstain fungi may cause “soft rot.”

4.2 WOOD-DESTROYING FUNGI

True wood destroyers possess enzyme systems which can hydrolyze cellulose and other polysaccharides of woody cells

into glucose and other simple nutrients, providing food for themselves. Many species in this group cannot reduce the lignin portion of the cell walls and, in the advanced stage of rot, the affected portion may be dry and shrunken, often darker in colour and broken into small, crumbling, brick-shaped pieces, termed "brown cubical rot."

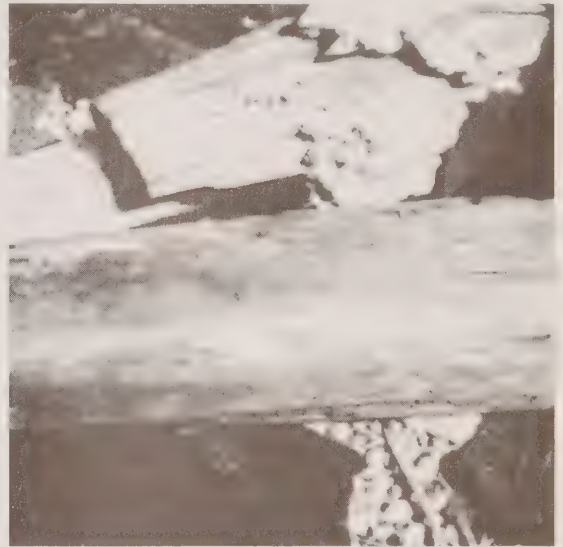
Other wood destroyers not only attack cellulose but also can break down lignin with oxidizing enzymes. These rots are more varied. They may be fibrous and stringy. Discrete concentric pockets of this type of fungus may be surrounded by firm wood which appears pitted or honeycombed. Sometimes a mottled appearance or soft spongy mass develops. These rots are usually lighter in colour than surrounding wood and are termed "white rots."



White Rot

Under wet conditions a deterioration of the surface of wood resembling brown rot may occur. This condition, called "soft rot" or "wet rot," is caused by growth of certain microorganisms, (including bacteria and fungi) in the superficial layers of wood and does not proceed as rapidly as in other types of fungal rot. The product of this rot is an amorphous surface or mass having the consistency of wet humus.

Most fungi which destroy wood show preference in the type of wood they attack. Some knowledge of this, plus a general knowledge of fungi appearance, can greatly assist in estimating the extent of damage to a structure. From the scores of fungi present in rotting wood, the most common species found in Canada have been selected for reference. Their pattern of attack is characteristic of the rot type to which they belong.



Soft or Wet Rot

4.2.1 Brown Pocket Rot – *Lenzites trabea*, Pers. and *L. Saepiaria*, Fr

Two species of brown pocket rot are discussed under this heading because they are similar in decay activities and appearance and world-wide in occurrence. This brown, cube-shaped rot occurs occasionally in hardwoods and more frequently in softwoods. It attacks dead timber in the forest and wood in service. Damage is extensive in exposed wood, poles, posts and ties, and in exposed situations in buildings. Decayed wood breaks into small cubical pieces, sometimes with thin strands of brown mycelium. As with brown cubical rots, this decayed material seriously weakens the host. *Lenzites trabea* is resistant to certain preservatives containing arsenic and pentachlorophenol. A garlic-like odour is sometimes perceived when timber treated with some arsenic-based preservatives is colonized by the fungus.



Brown Pocket Rot

built with softwood, dry rot must be considered the principal foe of the conservationist.

5.0 TREATMENT OF FUNGI

With care and attention to the physical environment of buildings and structures, damage due to fungal decay can be reduced or eliminated.

The most effective means of preventing fungal decay in wood structures is to create conditions which are unfavourable to their growth. This can be done by:

- a. repairing all water entry points to the building from above or below;
- b. drying out the structures by opening old vents or creating new ones;
- c. removing piled up earth and waste materials from the proximity of the building;
- d. disposing of decayed material; and
- e. applying a suitable chemical preservative treatment to the wood (see Vol. IV.4.2.1 "Wood Structures: Chemical Consolidation").

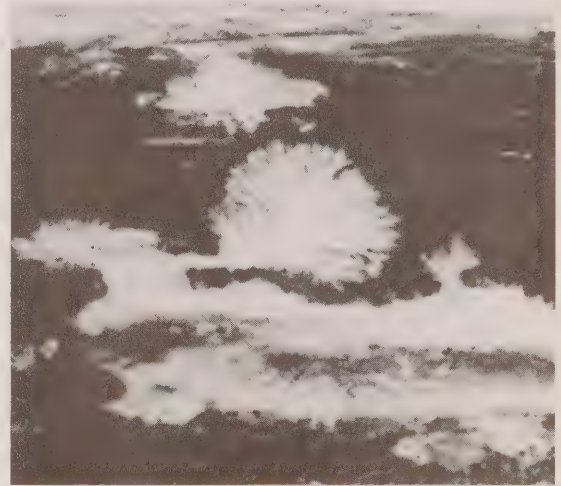
4.2.2 Dry Rot – *Merulius Lacrymans*, (Wulf) Fr. and *Poria Incrassata* (B. and C.) Curt

Merulius lacrymans and *Poria incrassata* both cause a similar type of brown cubical rot known as "building-rot." It occurs mainly on coniferous timbers in service in damp, unventilated situations.

These two species cause the most extensive losses from decay in wooden buildings in North America. Once established, the decay can spread rapidly. Early infection is often invisible.

Merulius lacrymans occurs primarily in eastern Canada and the northern United States, whereas *Poria incrassata* is reported more commonly in the Pacific Coast region and in the southern United States.

Dry rot is very difficult to eradicate because of the ability of strands to penetrate and survive for long periods in masonry and plaster. It occurs universally and can reappear momentarily wherever conditions favouring its growth are allowed to develop. Since most historic structures in North America are



Dry Rot

6.0 APPENDIX: IDENTIFICATION OF FUNGI

DIAGNOSTIC GUIDE CHART FOR MOULDS, SAPSTAINS AND FUNGI

MOULDS

COLOUR OF WOOD	DAMAGE	FRUIT BODY AND TYPE	NAME
Various shades, green predominant, black common.	Slight discolouration of wood, usually easily removed by brushing. Permeability and drying rate of timber slightly increased. No significant structural damage. Attacks softwood and hardwood; outer surface only.	Very fine fungal growth on surface; erect microscopic hairlike structures give fuzzy appearance.	Aureobasidium species <i>Chaetominium penicillium</i>

SAPSTAIN FUNGI

COLOUR OF WOOD	DAMAGE	FRUIT BODY AND TYPE	NAME
Bluish-black stain varying to steel grey; also some brown shades with blue grey.	Stained wood may be 25 percent weaker than unstained wood; bending and compression strength not significantly affected. Permeability of wood is increased, preservatives are more easily leached out from stained areas; blue stained area may cause failure of paint films applied over them. Attacks softwood of practically all commercial wood species.	Sometimes mouldlike growth of causal fungi present on surface of timber but bluish stains are caused by brownish hyphae which penetrate deep into sap wood. (Reason for colour appearance not fully understood.)	<i>Ceratocystis</i> species, (formerly known as <i>Ceratostomella</i>) <i>Cladosporium</i> , <i>Diplodia</i> , <i>Graphium</i> , <i>Aeternaria</i>

6.0 APPENDIX: IDENTIFICATION OF FUNGI
DIAGNOSTIC GUIDE CHART FOR MOULDS, SAPSTAINS AND FUNGI

WOOD-DESTROYING FUNGI

A: Principally Attacking Wood in the Forest

COLOUR OF WOOD	DAMAGE	FRUIT BODY AND TYPE	NAME
At early stages, pinkish to reddish-purple stains; advanced stage, whitish.	Small spindle-shaped cavities often filled with whitish fibrous material. Attacks softwood.	Bracket-like fruit body, often seen on trees, has grey-brown upper surface, yellow-brown below.	<i>Fomes pini</i> Karst. White pitted rot white pocket rot conk rot
White with narrow black lines, and a brownish zone bordering regions of advanced decay (may be whitish to yellowish).	Spongy or stringy mass of whitish decayed wood. Wood surface remains unchecked; no shrinkage or collapse until the decay is very advanced. Generally attacks hardwood, occasionally softwood.	Fruit body shelf- or hoof-shaped. Upper surface greyish to black, ridged or cracked; under-surface rusty brown or whitish with fine circular pore mouths.	<i>Fomes igniarius</i> (L. ex. Fr.) Kickx <i>Polyporus versicolor</i> (L.) white trunk rot white heart rot
Yellowish.	Decayed wood is very soft and light. Generally attacks hardwood; common in birch, beech, maple and poplar.	Hard grey "hooflike" fruit body. Pored undersides of a greyish buff colour; mycelium buff coloured.	<i>Fomes fomentarius</i>
Incipient decay shows as fire-red-brown stain often in streaks, and on end grain radiating from heart as series of reddish-brown rays.	Decay takes out heartwood; in advanced decay the cross section of the trunk cavity reveals an asterisk or starlike pattern of attack starting at the pith. Attacks softwood, common in forests and downed timber; common in balsam fir and spruce.	Fruit bodies are thin, leathery sheets with upper part curled to form small shelf. If bruised or cut, a fresh fruit body will exude a blood-red juice (hence the Latin species name). Mycelium white. Fruit bodies grey or grey-buff.	<i>Stereum sanguinolentum</i> (Alb. and Schw. ex Fr.) Fr. red heart rot red-brown stain
Incipient decay, yellowish to yellow-brown, occasionally with blackened areas.	Decayed wood breaks into small cubical pieces; the decayed material is seriously weakened. Usually attacks softwood, occasionally hardwood. Will attack in forest but more usually in cut timber, dead wood and timber in service.	Fruit bodies may be semi-circular or narrow shelf-like with velvety, cinnamon-brown upper surface and yellow-brown below. Radiating gills or irregular pores. Tough woody texture to some fruit bodies. Mycelium thin brown strands.	<i>Lenzites trabea</i> Pers. <i>Lenzites saepiaria</i> Fr. brown pocket rot

6.0 APPENDIX: IDENTIFICATION OF FUNGI
 DIAGNOSTIC GUIDE CHART FOR MOULDS, SAPSTAINS AND FUNGI

WOOD-DESTROYING FUNGI

B: Principally Attacking Wood in Service

COLOUR OF WOOD	DAMAGE	FRUIT BODY AND TYPE	NAME
Decayed wood breaks up into pale brown or medium brown cubical fragments.	Decayed wood breaks into small cubical pieces; decayed material is seriously weakened, very light in weight and crumbles between the fingers. Attacks softwood most frequently but also hardwood; attacks timber in buildings.	Thick luxuriant masses of white mycelium like cotton wool or snowdrifts under ideal conditions. Pencil thick greyish strands, will often penetrate masonry. Maturer mycelium grey silky skin with lilac and yellow tinges. Fruit bodies fleshy, rather tough, shaped like a pancake or bracket. Spore surface wrinkled into pores rusty-red with grey edges. Surroundings coated with the millions of red-brown spores produced. Strands or rhyzomorphs are brittle on drying and are easily snapped between the fingers.	<i>Merilius lacrymans</i> (Wulf) Fr. building dry rot dry rot brown cubical rot
Decayed wood breaks up into pale brown or medium brown cubical fragments.	Decayed wood breaks into small cubical poeces. The decayed material is seriously weakened. Attacks softwood most frequently but also hardwood. Attacks timber in buildings.	Whitish sheets of mycelium, thin strands or rhyzomorphs, flexible when dry. Fruit bodies orange to olive-coloured pored plates.	<i>Poria incrassata</i> (B and C) Curt. building dry rot dry rot brown cubical rot
Same as above.	Same as above.	Whitish cottony sheets of mycelium with no bright colours. Rhyzomorphs thin, whitish strands, flexible when dry. Fruit bodies soft whitish plates covered with minute pores. Strands flexible when dry.	<i>Poria vaillantii</i> building dry rot dry rot
Purplish grey to grey-black.	Wet surface wood decayed and easily scaped off underlying softwood. Forms small cuboid patterns when surface dries.	Fungal mycelium and fruiting bodies not usually observed.	Bacteria, moulds and sapstain fungi soft rot wet rot

7.0 BIBLIOGRAPHY

Cooney, D.G., and R. Emerson. 1964. *Thermophilic Fungi*. Freeman and Co., London.

Hickin, H.E. 1972. *The Dry Rot Problem*. Hutchison and Co. Ltd., London.

U.S. Department of Agriculture. 1969. *Factors Influencing Decay of Untreated Wood*. U.S. Forest Products Laboratory, Forest Service Research Note FPL0154. Washington, DC.

_____. 1955. *Protection from Wood-Destroying Organisms*. Agricultural Handbook 72. Washington, DC, pp. 381-98.

Verral, A.F. 1968. *Poria Incrassata Rot: Prevention and Control in Buildings*. Technical Bulletin 1385. U.S. Department of Agriculture, Washington, DC.

Illustrations are the property of the Heritage Conservation Program, unless otherwise noted.

VOLUME VI

CONSERVATION OF MATERIALS

5.5

WOOD

DAMAGE BY INSECTS AND MARINE BORERS

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: D.P. OSTAFF

CONTENTS

1.0 INTRODUCTION

2.0 IDENTIFICATION AND TREATMENT

3.0 INITIAL INSECT ATTACK IN UNSEASONED WOOD

- 3.1 AMBROSIA BEETLES – TRYPODENDRON
SP. – ADULTS
- 3.2 FLAT-HEADED OR METALLIC WOOD
BORERS – BUPRESTIDAE – LARVAE
- 3.3 HORNTAILS – SIREX SPP., UROCERUS SSP.
– LARVAE
- 3.4 ROUND-HEADED WOOD BORERS –
MONOCHAMUS SPP., TETROPIUM SPP. –
LARVAE
- 3.5 SHOT-HOLE BORERS – BOSTRYCHIDAE
LARVAE AND ADULTS

4.0 INITIAL INSECT ATTACK IN SEASONED WOOD OR WOOD IN SERVICE

- 4.1 CARPENTER ANTS – CAMPONOTUS SPP. –
WORKERS
- 4.2 CARPENTER BEES – XYLOCOPA
VIRGINICA DRURY
- 4.3 DEATH-WATCH BEETLES – TESTOBIUM
RUFOVILLOSUM, DE GEER – LARVAE
- 4.4 FURNITURE BEETLES – ANOBIUM
PUNCTATUM DE GEER, HADROBREGMUS
SPP. – LARVAE
- 4.5 OLD HOUSE BORERS – HYLOTRUPES
BAJULUS (L.) LARVAE AND ADULTS
- 4.6 POWDER-POST BEETLES – LYCTUS SPP. –
LARVAE
- 4.7 TERMITES – DAMPWOOD –
ZOOTERMOPSIS SPP. – IMMATURE FORMS
(NYMPHS)
- 4.8 TERMITES – DRYWOOD –
CRYPTOTERMES BREVIS (WLK.),
KALOTERMES SPP. – NYMPHS
- 4.9 SUBTERRANEAN TERMITES –
RETICULITERMES SPP. – WORKERS
- 4.10 WHARF BORERS –
NACERDES MELANURA (L.) LARVAE
- 4.11 WOOD-BORING WEEVILS –
CURCULIONIDAE – ADULTS AND LARVAE

5.0 DIAGNOSTIC CHARACTERISTICS OF MARINE BORERS

- 5.1 GRIBBLE – LIMNORIA SPP. – ADULTS
- 5.2 SHIPWORMS – BANKIA SPP., TEREDO SPP.
– ADULTS

6.0 ACKNOWLEDGEMENTS

7.0 BIBLIOGRAPHY

1.0 INTRODUCTION

Insect attack is a serious form of degradation in wood in service. Recognition and prevention of insect attack is particularly important to the preservation of historic buildings. This article provides a brief introduction to the agents responsible, including beetles (Coleoptera); ants, bees and wasps (Hymenoptera); termites (Isoptera); and marine borers (Crustacea and Mollusca). The information deals with the insect or borer causing the damage, a description of the damage, type of wood attacked and possible treatments. However, the material provided here is necessarily brief. Specialized written sources should be studied and expert advice should be sought when insect infestation of wood is suspected.

Generally, insect attack is of two types: one in which the initial attack occurs in unseasoned wood, another where insects attack seasoned wood.

Where initial attack occurs in unseasoned wood, active infestations normally persist only in very new structures. Treatment is not likely to be necessary when signs of this type of attack are found in historic buildings, except with the introduction of new components.

Where initial attack occurs in seasoned wood or wood in service, a new agent is probably involved and active infestation may persist or recur. Treatment of this type of attack through proper identification and elimination of the agent responsible is essential.

2.0 IDENTIFICATION AND TREATMENT

Before any treatment for insect attack can be recommended, one must know the causal agent. A fairly accurate identification can be made by noting the following characteristics:

- type of wood attacked
- age of wood
- type of damage
- consistency of boring dust (frass).

After determining the nature of the infestation, the attack should be identified as active or completed. Symptoms of active infestation include piles of boring dust, fresh, clean-looking exit holes and live insects. To make a positive identification of the causal agent, it is essential to possess an insect specimen. Following positive identification, treatment may be recommended.

Cautions:

- Before using pesticides, check with Agriculture Canada for the chemical registered for the intended purposes (these tend to change with new information from year to year).
- When using pesticides, follow the manufacturer's instructions carefully and wear protective clothing, rubber gloves and a respirator.
- Fumigation should be done only by a licensed applicator. Fumigation does not prevent re-infestation.

3.0 INITIAL INSECT ATTACK IN UNSEASONED WOOD

Insect attack in this category consists of small, round "pin-holes" up to 3 mm in diameter, or large, elliptical or circular holes 3 mm to 10 mm (occasionally larger) made by larvae mining in solid wood, or adults emerging after completion of larval stage.

Damage occurs when adult beetles or horntails deposit eggs into recently felled, fire- or insect-killed timber, unseasoned lumber or occasionally, standing green trees. Larvae usually mine the cambium (inner bark), finally penetrating the solid wood and constructing extensive mines. Both hardwoods and softwoods are attacked.

Active infestations usually occur in newly built structures as a result of using wood infested with insects prior to manufacture. These insects do not normally re-infest wood and control measures are unnecessary for wood in service.

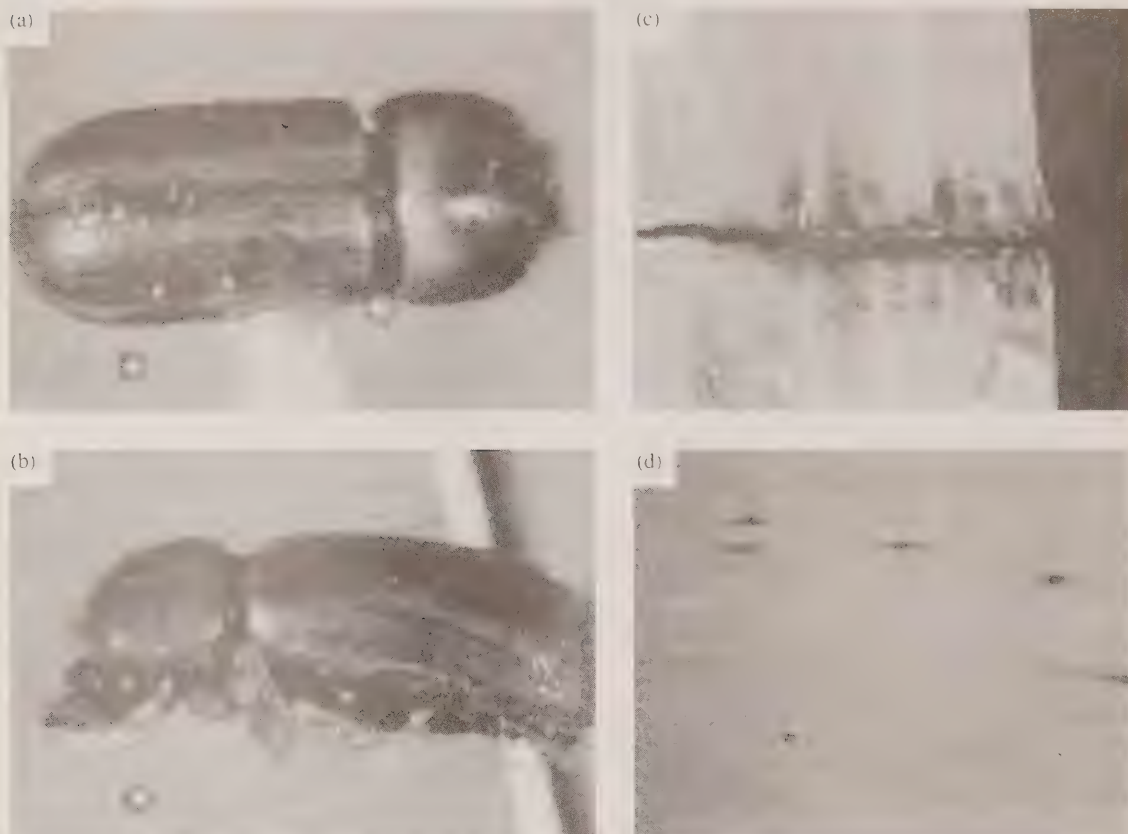
3.1 AMBROSIA BEETLES – TRYPODENDRON SP. – ADULTS

- a. Damage:

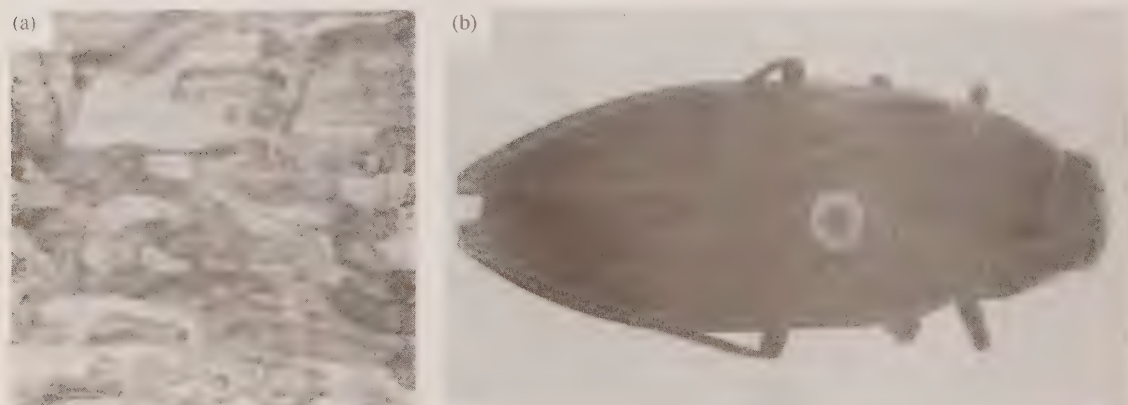
Small, round pin-holes 3 mm with dark stained walls, occasionally stain in form of streaks running parallel to grain; no boring dust in galleries.
- b. Remarks:

Adult beetles attack recently felled logs, unseasoned lumber (both hardwoods and softwoods); neither larvae nor adults feed on wood; infestation ceases when lumber dries out. Will not re-infest.
- c. Treatments and cautions:

No action necessary; remove holed timber if appearance unacceptable.



Ambrosia Beetles: a) Adult beetle, Trypodendron sp., dorsal view. b) Lateral view. c) Damage in spruce: note central gallery with lateral branches, stained gallery walls. d) Pin-holes in yellow birch: note stain around holes.



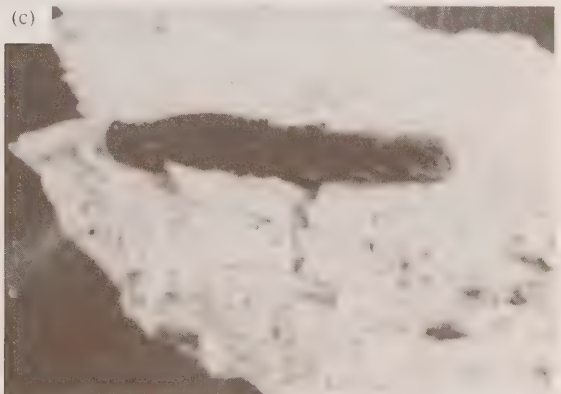
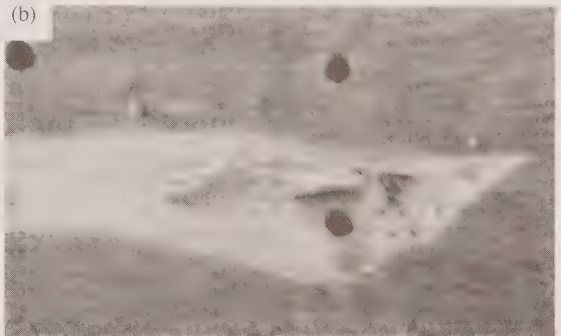
Flat-headed or Metallic Wood Borers: a) Buprestid attack: note scoring of outer sapwood. b) Adult beetle: note typical "bullet" shape.

3.2 FLAT-HEADED OR METALLIC WOOD BORERS – BUPRESTIDAE – LARVAE

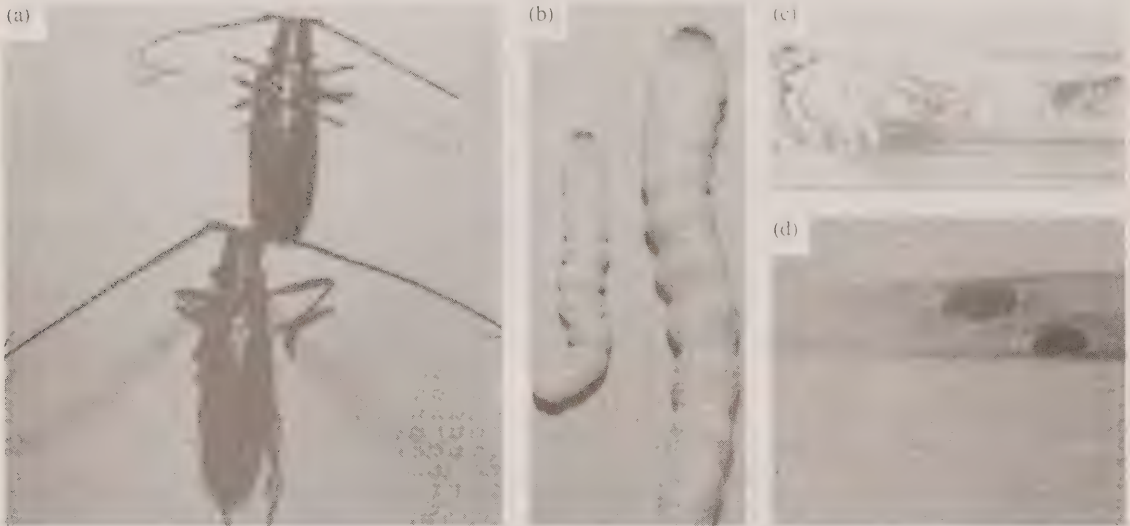
- a. Damage:
Usually confined to outer sapwood; galleries tightly packed with boring dust (mixture of fine powdery material speckled with brown particles due to feeding in bark); oval exit holes made by emerging adult.
- b. Remarks:
Adult beetles deposit eggs in recently felled or killed timber. Will not re-infest
- c. Treatments and cautions:
No action necessary; remove holed timber if appearance unacceptable.

3.3 HORNTAILS – SIREX SPP., UROCERUS SSP. – LARVAE

- a. Damage:
Galleries circular in cross section, very tightly packed with fine boring dust, extensive excavations; adults make circular exit holes 3-10 mm in diameter.
- b. Remarks:
Larvae present in green or recently felled or killed timber (hardwoods and softwoods); active infestations only in newly constructed buildings. Will not re-infest.
- c. Treatments and cautions:
No action necessary; remove holed timber if appearance is unacceptable.



Hornails: a) Adult, Urocerus sp. b) Adult flight holes c) Gallery system: note extensive mining and densely compacted frass.



Courtesy Forintek Canada Corp.

Round-headed Wood Borer: a) Adult female *Monochamus scutellatus*, upper; Adult male, lower: note longer antennae on male. b) Early and late instar larvae. c) Gallery pattern: note excelsior-like shavings. d) "Worm-holes" in lumber.

3.4 ROUND-HEADED WOOD BORERS – MONOCHAMUS SPP., TETROPIUM SPP. – LARVAE

- a. Damage:
Oval holes 6-12 mm in diameter made by larvae; galleries oval in cross section, winding irregularly through wood, packed with excelsior-like boring dust; adult emergence holes circular, 6-12 mm in diameter.
- b. Remarks:
Attacks recently-felled, insect- or fire-killed timber (softwoods); active infestations only in newly constructed structures. Adults need bark to deposit eggs. Will not re-infest.
- c. Treatments and cautions:
No action necessary; remove holed timber if appearance unacceptable.



Shot-hole Borers: Adult beetle: note head not visible from above.

3.5 SHOT-HOLE BORERS – BOSTRYCHIDAE LARVAE AND ADULTS

- a. Damage:
Small circular holes 2-6 mm in diameter. Galleries, circular in cross section, tightly packed with fine boring dust.

b. Remarks:

Recently felled or seasoning timber attacked (usually sapwood of hardwoods but sometimes in softwoods); seasoned timber and timber of low moisture content generally not attacked. Damage resembles *Lyctus* spp. (4.6 below), holes are generally larger, frass more coarse and tightly packed. Will not re-infest.

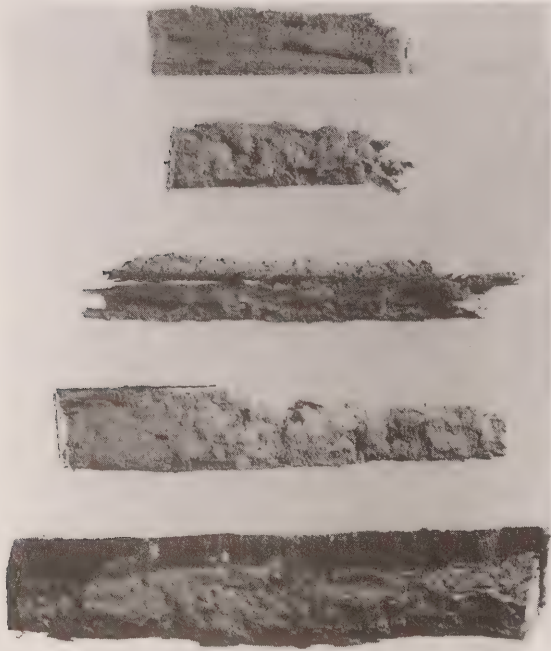
c. Treatments and cautions:

Logs should be protected by either debarking, water sprinkling, ponding or spraying with suitable chemical insecticide. Manufactured products should be protected by fumigation, treatment with residual insecticides or replacement of wood if infestation extensive.

softer layers of the wood have been eaten away, leaving larger irregular galleries free of bore dust.

These two types of damage occur in both hardwoods and softwoods and can be found in furniture, structural timbers or other manufactured articles. The first indications of damage are small round pin-holes on the surface, often with small piles of fine boring dust accumulating around holes or under infested material.

Eventually the strength of infested timber is so far depleted that structural members become seriously weakened and sag, shake or collapse. Infestations should therefore be accurately identified and promptly treated to avoid serious structural damage.



Shot-hole Borers: Damage in mahogany lumber.

4.0 INITIAL INSECT ATTACK IN SEASONED WOOD OR WOOD IN SERVICE

Damage in seasoned wood can be classed as powdering, where in the final condition of the wood, an outer shell remains with the inside of the wood reduced to a powder as a result of feeding by larval stages and layering, where the

4.1 CARPENTER ANTS – *CAMPONOTUS* SPP. – WORKERS

a. Damage:

Galleries with clean, smooth walls; the softer springwood eaten, giving wood a “honey-combed” appearance; shredded wood particles ejected from galleries.

b. Remarks:

All species of wood, including cedar, can be attacked; carpenter ants do not feed on wood which is used only as a nest. Carpenter ants resemble adult termites but differ by having elbowed antennae (termites have beaded antennae), hind wings smaller than fore wings (termites have equal-sized wings), a constricted area between thorax and abdomen (not in termites). Will re-infest.

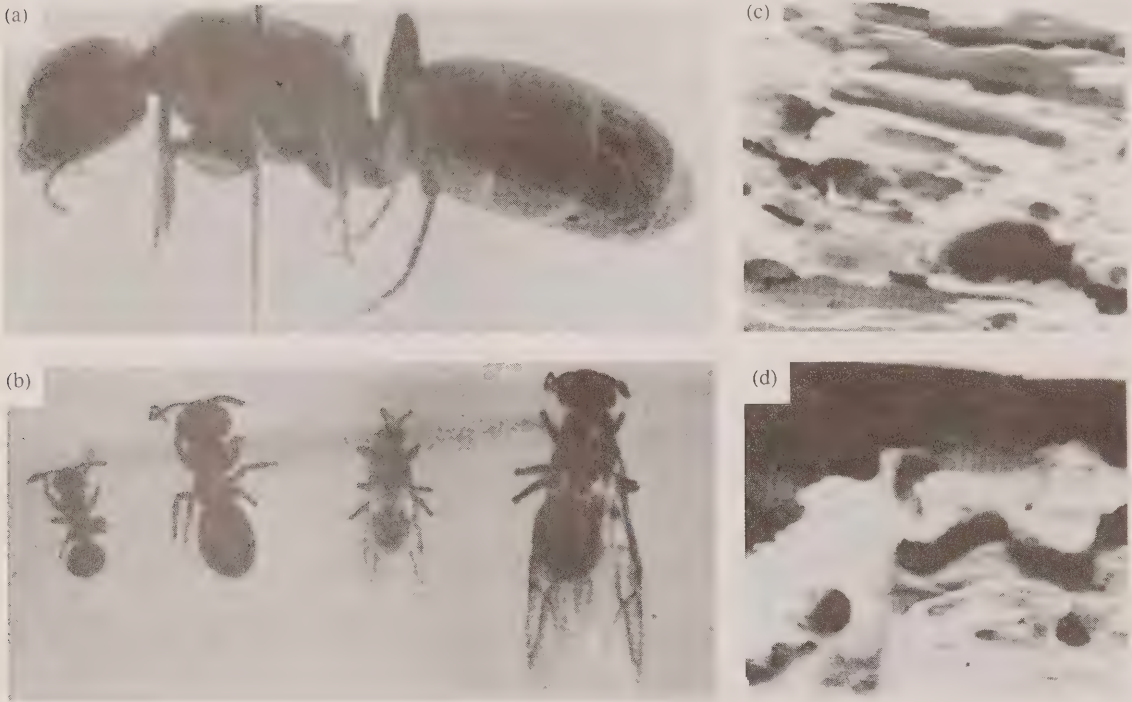
c. Treatments and cautions:

If nest can be located, drill a hole into the cavity and inject a recommended chemical dust formulation indoors; oil-based or emulsion formulation outdoors. When the nest cannot be located, apply a residual contact insecticide to ant runways. Treatment should be repeated after the residual period (usually six weeks), until no ants are seen. Caution: oil-based formulations can damage plants and shrubs.

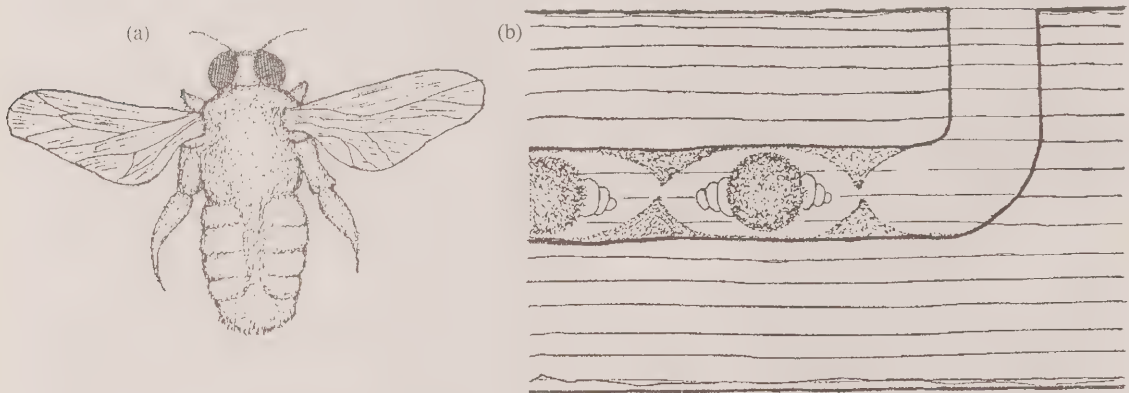
4.2 CARPENTER BEES – *XYLOCOPA VIRGINICA* DRURY

a. Damage:

Perfectly circular holes 10 mm in diameter penetrating to a depth of ca .25 mm; horizontal galleries excavated 15-20 cm perpendicular to entrance holes.



Carpenter Ants: a) Adult female *Camponotus pennsylvanicus*. b) Colony of *C. nova boracensis*: two workers, adult male and larger adult female. c) Termite damage. d) Carpenter ant damage: note clean-walled galleries of carpenter ants.



Carpenter Bee: a) Adult bee *Xylocopa* sp. b) Damage.

b. Remarks:

Excavations always in well-lighted areas and in a horizontal position in wood. Wood chosen is soft and easy to work, such as redwood, cedar, white pine, and well-weathered wood.

c. Treatments and cautions:

Inject an insecticide into entrance holes, plug holes with plastic wood or similar material and spray entire area with a residual chemical insecticide.

naked eye; fresh flight holes are sharp in outline and wood within is fresh and bright; internal disintegration usually severe.

b. Remarks:

Attack mostly in hardwoods, especially oak; attack often associated with fungal attack; common in old buildings. Will re-infest.

c. Treatments and cautions:

Remedy structural defects causing accumulation of moisture; provide adequate ventilation; provide vapour barrier as for Furniture Beetle (see 4.4 below); replace infested wood with treated wood (dip, brush or spray); remove decayed wood and bore dust; spray with residual contact insecticides with good penetrating powers.



Death-watch Beetle: *Xestobium rufovillosum*.

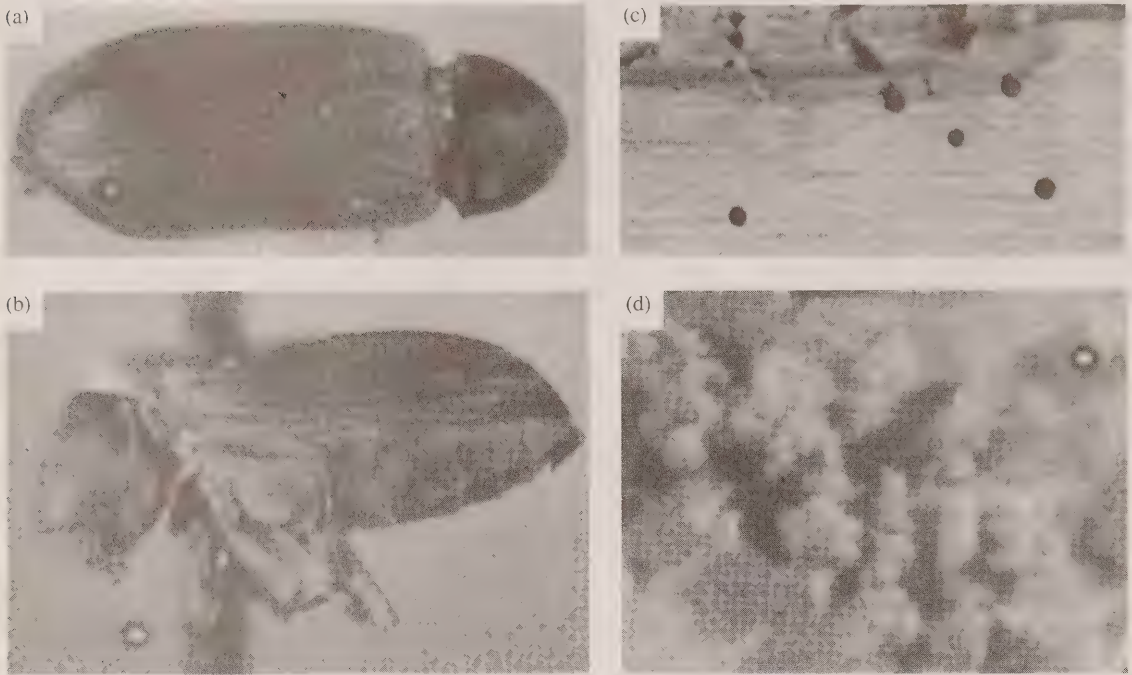
4.3 DEATH-WATCH BEETLES – TESTOBIMUM RUFOVILLOSUM, DE GEER – LARVAE

a. Damage:

Circular flight holes 3 mm in diameter; galleries with large bun-shaped pellets easily visible to the



Death-watch Beetle: Damage



Furniture Beetles: a), b) Adult *Anobium punctatum*, (a) dorsal and (b) lateral views.
c) Flight holes and internal disintegration of sapwood. d) Frass: note ellipsoidal pellets.

4.4 FURNITURE BEETLES – ANOBIUM PUNCTATUM DE GEER, HADROBREGMUS SPP. – LARVAE

- a. Damage:
Circular flight holes 1.6 mm in diameter; galleries numerous, running in all directions, often merging; loosely packed frass with small, gritty ellipsoidal pellets; damage usually detected in homes older than 10 years.
- b. Remarks:
Infestations usually begin in crawl spaces or in wood near ground; softwoods and hardwoods attacked; three or more exit holes per 20 cm², or some pinsized parasite exit holes indicate old well-established infestations. Will re-infest.
- c. Treatments and cautions:
Thoroughly spray wood surface in crawl space with recommended contact insecticides; limit moisture supply beneath infested buildings by covering with 0.175 mm polyethylene plastic or roll roofing; fumigation may be the only choice for severe,

widespread infestations. Fumigation does not prevent re-infestation. Some fumigants will react with other materials causing odours or deleterious effects.

4.5 OLD HOUSE BORERS – HYLOTRUPES BAJULUS (L.) LARVAE AND ADULTS

- a. Damage:
Adult exit holes and larvae feeding tunnels oval, 6 mm in diameter; galleries near surface of wood results in rippled appearance and light coloured streaks.
- b. Remarks:
Softwoods only attacked; prefer recently seasoned wood but may continue for 10 or more years. Will re-infest. No documented cases of old house borer in Canada, but has potential of becoming a very serious pest of softwoods in buildings.
- c. Treatments and cautions:
Control directed to softwoods only; small exposed infestations may be treated with residual contact insecticides; widespread infestations may require fumigation.

(a)



(b)



(c)



Courtesy of Forintek Canada Corp.

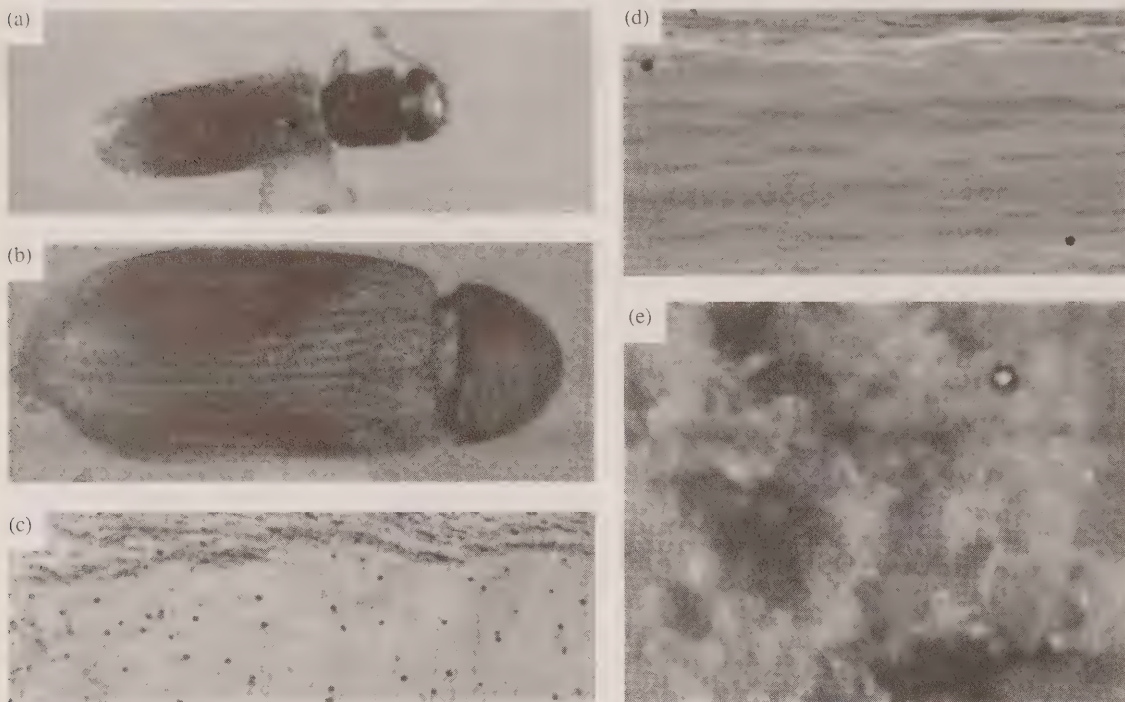
Old House Borer: a) Adult Hylotrupes bajulus. b) Larvae. c) Damage to roof timbers.

4.6 POWDER-POST BEETLES – LYCTUS SPP. – LARVAE

- a. Damage:
Small circular flight holes 2 mm in diameter; galleries loosely packed with fine talcum-like boring dust.
- b. Remarks:
Attacks only hardwoods with pore size large enough to accommodate ovipositor greater than 0.055 mm; usually confined to sapwood with high starch content. Will re-infest.
- c. Treatments and cautions:
If possible, remove and replace infested material. For infestations in parquet floors, mop small areas with recommended oil-base formulations. Putty existing holes; fumigate only if infestation is large and removal and replacement costly. Some oils may affect glue backing on flooring; finish may soften or blister and require refinishing.

4.7 TERMITES – DAMPWOOD – ZOOTHERMOPSIS SPP. – IMMATURE FORMS (NYMPHS)

- a. Damage:
Wide, shallow tunnels, usually forming soft rings; tunnels separated by septa of wood; large wet pellets of coarse, compacted material excreted; wood entirely consumed.
- b. Remarks:
In damp or decayed wood; found only on west coast of British Columbia; chiefly in softwoods. Will re-infest.
- c. Treatments and cautions:
Eliminate source of moisture causing wood to be damp; treat with a recommended fungicide to arrest fungal activity; pour or inject a residual contact insecticide into galleries.

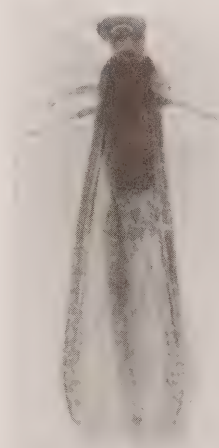


Photos c) and d) Courtesy of Forintek Canada Corp.

Powder-post Beetles: Adult lyctid beetle (a), compared to anobiid beetle (b). c) Damage in Maple. d) Damage in oak flooring. e) Mixture of anobiid and lyctid frass; lyctid frass flour-like, anobiid, gritty ellipsoidal pellets.

4.8 TERMITES – DRYWOOD – CRYPTOTERMES BREVIS (WLK.), KALOTERMES SPP. – NYMPHS

- a. Damage:
Broad pockets or chambers connected by small diameter tunnels cut across grain of wood; galleries clean, excrement ejected through small openings in wood; damage in dry sound wood.
- b. Remarks:
Wood openings sealed with a paper thin, cement-like pus secreted by termites; faecal pellets seed-like, hard, with concave faces; chambers close to wood result in “blisters” or thin films of wood. Will re-infest. Infestations in Canada usually in imported material only.
- c. Treatments and cautions:
Replace infested wood if possible. Inject insecticide (dust or liquid) into galleries where wood is not structurally weakened. Heavily infested structures may require fumigation.



Dampwood Termites: Adult dampwood Zootermopsis.



Drywood Termites: Furniture damage: note internal disintegration.

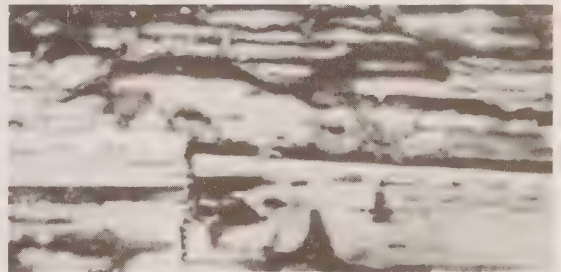
4.9 SUBTERRANEAN TERMITES – RETICULITERMES SPP. – WORKERS

- a. **Damage:**
Wood entirely consumed, honeycombed appearance; walls of galleries spotted with damp masses of earth and excrement; mud galleries or shelter tubes constructed to reach uninfested wood.
- b. **Remarks:**
Attacks hardwoods and softwoods, moist, decayed wood close to or in contact with ground; prefers springwood of softwoods; maintains contact with nest (usually in soil) through earthen shelter tubes. Will re-infest.
- c. **Treatments and cautions:**
Avoid or eliminate all wood and soil contact; repair source of dampness; remove any buried or piled wood which may serve as a food source; use registered insecticides injected into the soil around the perimeter of wooden structures down to the foundation to form a toxic barrier to termites. (This is usually done by licensed pest control operators.)



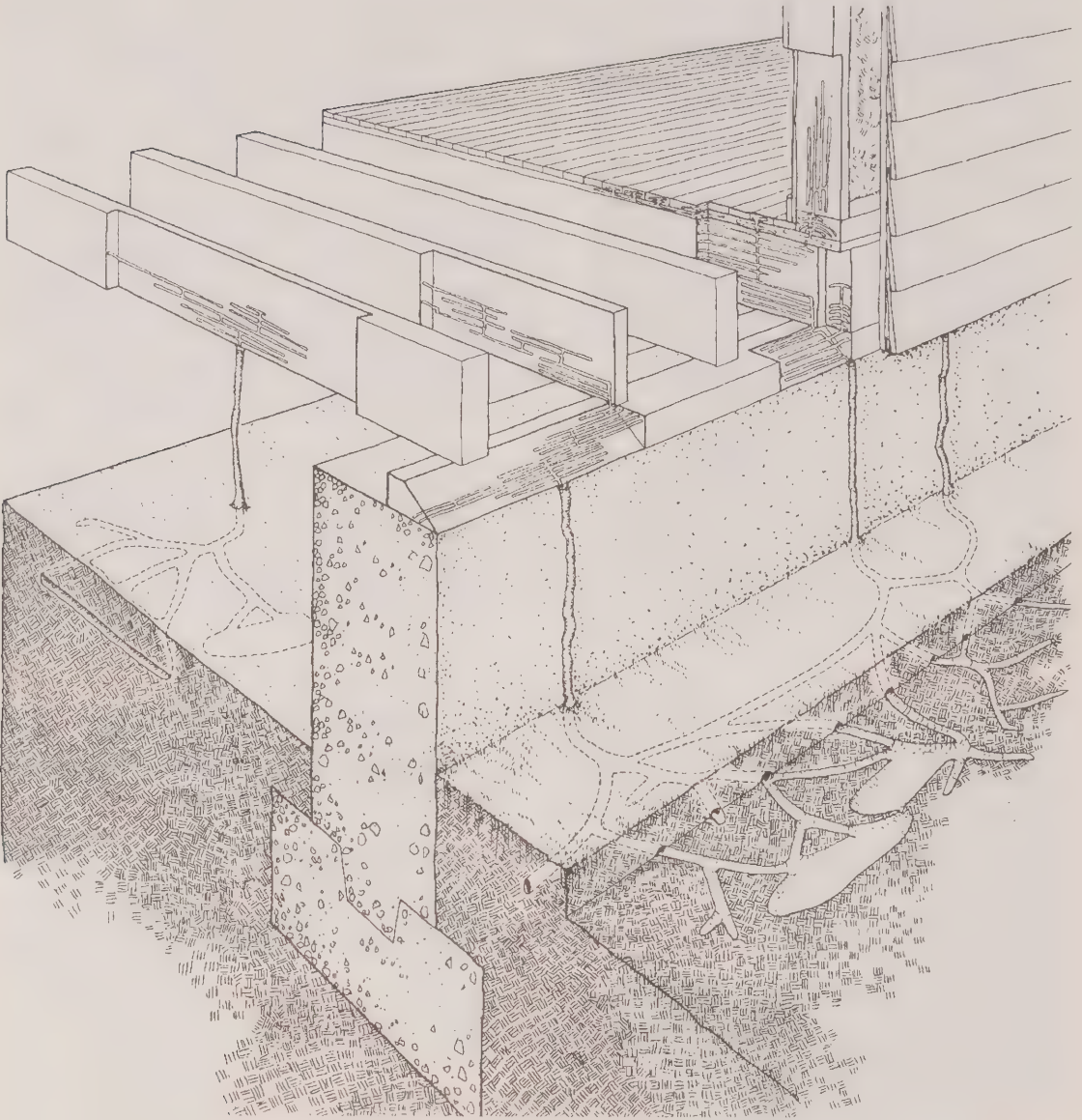
Courtesy of Forintek Canada Corp.

Subterranean Termites: Members of Reticulitermes sp. colony; workers, soldiers, winged nymph.

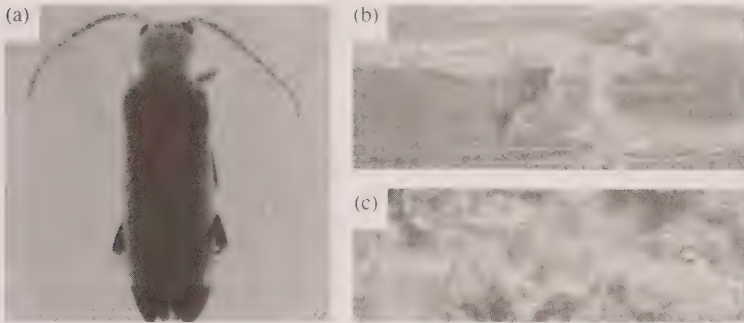


Courtesy of Forintek Canada Corp.

Subterranean Termites: Damage: note gallery walls spotted with excrement.

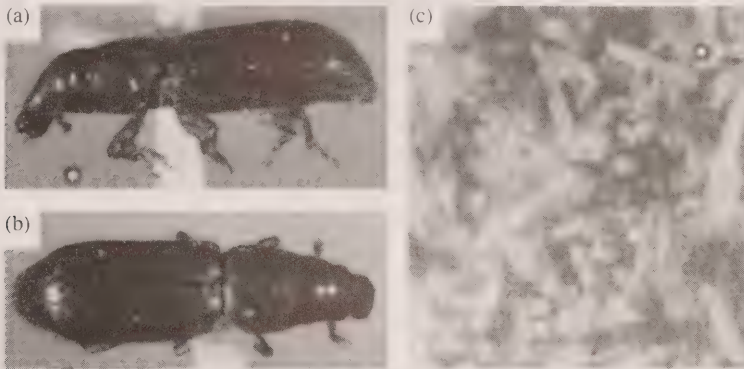


Subterranean Termites: c) Typical termite activity in structures: note "tubing" to reach wood.



Courtesy of Forintek Canada Corp.

Wharf Borer a) Adult Nacerdes melanura. b) Gallery: note the packed galleries and fungal decay of wood. c) Frass, a damp mass of shavings.



Wood-boring Weevils: a) Adult weevil, lateral view. b) Dorsal view: note "snout" characteristic of weevils. c) Frass, fine with individual granules.

4.10 WHARF BORERS - NACERDES MELANURA (L.) LARVAE

- a. Damage:
Oval enlarged cavities with grain, plugged with damp mass of coarse pellets and shavings; no definite sized or shaped galleries.
- b. Remarks:
Found mainly in softwoods but occasionally hardwoods (especially oak); in damp or wet wood in the process of fungal decay; common in wharf timbers, piling between flooding and high-water level. Will re-infest.
- c. Treatments and cautions:
Correct damp or wet conditions; replace infested wood with pressure treated timber; treat infested wood with fungicide to arrest fungal activity.

4.11 WOOD-BORING WEEVILS - CURCULIONIDAE - ADULTS AND LARVAE

- a. Damage:
Galleries smaller than Anobium (see 4.4 above), usually parallel to wood surface; boring dust finer in texture with individual granules more circular; flight holes slightly oval with a ragged or indistinct margin, constructed at an angle 45° to surface.
- b. Remarks:
Softwoods and hardwoods, including plywood attacked; usually associated with fungal decay. Will re-infest.
- c. Treatment and cautions:
Eliminate source of moisture contributing to fungal attack; provide adequate ventilation; treat wood with a recommended fungicide; remove and replace infested wood with treated wood if attack extensive.



Gribble: a) Adult marine *Limnoria* sp. b) Damage to piles showing characteristic "waisted" effect at water level.

Courtesy of BC Research Corp.

5.0 DIAGNOSTIC CHARACTERISTICS OF MARINE BORERS

Marine structures and sawlogs stored in seawater awaiting use are subject to rapid and extensive damage by wood-boring animals, known as marine borers.

Two distinct types of marine borers exist on the east and west coasts of Canada. Members of the wood-boring 'Crustacea,' commonly called gribble or pin worm, are equipped with several pairs of legs and are distantly related to the crab and wood louse. Members of the 'Mollusca,' commonly referred to as shipworm or 'teredo,' are bivalves distantly related to clams and oysters.

Water temperature, salinity, an adequate supply of oxygen and a source of food are factors affecting the incidence and prevalence of marine borers.

5.1 GRIBBLE – LIMNORIA SPP. – ADULTS

- a. Damage:
Network of small-diameter, short tunnels just below wood surface; erosion by wave-action at waterline gives vertical timbers an "hour-glass" appearance.
- b. Remarks:
Attacks hardwoods or softwoods in marine environments; damage occurs from erosion of galleries at waterline.
- c. Treatments and cautions:
Timbers should be removed and replaced with timbers pressure treated with creosote.



Courtesy of BC Research Corp.

Shipworm: a) Mouth of adult *Bankia setacea*; note grinding mandibles used to make galleries. b) Galleries in wood; note whitish walls with calcium deposit. c) Creosoted piling showing little exterior signs of attack but with extensive burrows in interior (dia. may exceed 22 mm).

5.2 SHIPWORMS – *BANKIA* SPP., *TEREDO* SPP. – ADULTS

- a. Damage:
Small pin-holes 20 mm in diameter on outer surface made by settling larvae; galleries circular, increasing in size, coated with a calcium deposit.
- b. Remarks:
Hardwoods and softwoods exposed in salt water environments are attacked.
- c. Treatments and cautions:
Remove infested timber and replace with timber pressure treated with creosote.

6.0 ACKNOWLEDGEMENTS

DRAWINGS: Lise Potvin

PHOTOGRAPHS: Photos are the property of the author unless otherwise noted.

7.0 BIBLIOGRAPHY

- Bletchly, J.D.** 1969. *Insect and Marine Borer Damage to Timber and Woodwork: Recognition, Prevention and Eradication*. Her Majesty's Stationery Office, London.
- Bramhall, G.** 1966. *Marine Borers and Wooden Piling in British Columbia Waters*. Publication 1138. Canadian Forestry Service, Ottawa.
- Creelman, I.S.** 1972. *Control of Ants*. Dept. of Agriculture, Ottawa.
- Esenether, G.R., and D.E. Gray.** 1968. "Subterranean Termite Studies in Southern Ontario," *Canadian Entomologist*, Vol. 100, pp. 827-34.
- Fitzsimmons, K.R.** 1979. "Termite Control in Historic Landmarks," *Historic Preservation*, Vol. 22, No. 4. NTHP, Washington, DC, pp. 40-44.
- Hickin, N.E.** 1963. *The Insect Factor in Wood Decay*. 2nd edition. Hutchison and Co. Ltd., London.
- _____. 1971. *Wood-Destroying Insects and Works of Art*. New York Conference on Conservation of Stone and Wooden Objects. Vol. 2. 1970. Symposium 2. London, pp. 75-80.
- Johnston, H.R.** 1960. *Soil Treatments for Subterranean Termites*. Occasional Paper 152. U.S. Dept. of Agriculture, Washington, DC.
- _____, **V.K. Smith and R.H. Beal.** 1972. *Subterranean Termites, Their Prevention and Control in Buildings*. Home and Garden Bulletin No. 64. U.S. Dept. of Agriculture, Washington, DC.
- Moore, H.B.** 1978. "The Old House Borer, An Update," *Pest Control*, Vol. 46, No. 3, pp. 14-17, 52, 53; Vol. 46, No. 4, pp. 28, 30, 32, and Vol. 46, No. 5, pp. 26, 28.
- Ostaff, D.P.** 1974. *Ambrosia Beetles*. Information Report OPX99. Forest Products Laboratory, Ottawa.
- _____. 1974. *Carpenter Ants*. Information Report OPX101. Forest Products Laboratory, Ottawa.
- _____, and **J.K. Shields.** 1978. *Reduction of Losses to Logs and Lumber Caused by Wood-Boring Insects*. Information Report OPX218. Forest Products Laboratory, Ottawa.
- Ruppel, D.H.** 1973. *Termites in B.C.* Forest Pest Leaflet 57. Pacific Forest Research Centre, Victoria.
- _____. 1973. *Carpenter Ants*. Forest Pest Leaflet 58. Pacific Forest Research Centre, Victoria.
- Smith, D.N.** 1954. *Powder-Post Beetles in Structural Timber in Coastal B.C.* Publication 903. Dept. of Agriculture, Ottawa.
- Williams, L.H.** 1973. "Identification of Wood-destroying Beetles," *Pest Control*, Vol. 1, No. 5, pp. 30, 32, 34, 36, 38, 40.
- _____. 1973. "Recognition and Control of Wood-destroying Beetles," *Pest Control*, Vol. 1, No. 3, pp. 24, 26, 28.

VOLUME VI

CONSERVATION OF MATERIALS

5.6

WOOD

DAMAGE BY HEAT AND FIRE

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: P. STUMES

CONTENTS

1.0 INTRODUCTION

2.0 BASIC COMPOSITION OF WOOD

3.0 THERMAL PROPERTIES

- 3.1 THERMAL EXPANSION
- 3.2 SPECIFIC HEAT
- 3.3 EFFECTS OF MOISTURE CONTENT
- 3.4 THERMAL CONDUCTIVITY AND
RESISTANCE

4.0 THERMAL DEGRADATION

- 4.1 THE PROCESS OF DECOMPOSITION
AND BURNING
- 4.2 INFLUENCE OF DIMENSIONS
ON FIRE DANGER
- 4.3 CHARRING
- 4.4 EFFECTS OF WOOD TREATMENT

5.0 FIRE SAFETY PRECAUTIONS

6.0 POST-FIRE ACTIONS

7.0 BIBLIOGRAPHY

1.0 INTRODUCTION

From prehistoric times to the present wood has been used both as building material and as fuel.

In Canada a considerable number of historic structures are made entirely of wood. Masonry structures also contain a large amount of timber. Because wood is a relatively combustible material, it is extremely important that conservators of historic structures become familiar with the types of damage caused by heat and the methods to prevent fire.

The purpose of this article is to explain the behaviour of wood in fire. This will enable the conservator to develop effective alternative fire protection methods which are compatible with the special conditions of historic structures and satisfy the objectives of the applicable fire and safety codes.

In order to facilitate the understanding of the major points, certain scientific facts are somewhat oversimplified.



The Robert Service Cabin, Dawson, YT

2.0 BASIC COMPOSITION OF WOOD

Wood is an organic material, composed from several extremely complex polymers. The major elemental constituents of these polymers are:

Carbon	approx. 50%
Oxygen	approx. 40%
Hydrogen	approx. 6%

Elemental carbon and hydrogen will burn violently in the presence of oxygen. However, in wood these elements are combined into polymeric chains which do not burn at normal temperatures. The polymeric groups are the following:

Cellulose	45 – 60%
Hemicellulose	15 – 25%
Lignin	25 – 35%
Resins, etc.	approx. 5%

Cellulose and hemicellulose are the main ingredients of the woody cells which create the fibre-like structure of wood. Lignin can be thought of as the adhesive that holds the fibres together. The remaining components are nutrients and a variety of other ingredients, usually called resins.

When heat is applied to wood, some of these compounds evaporate in the form of gases and burn with visible flames. Other compounds, chiefly carbonaceous, remain solid and burn as glowing or smoldering char.

Wood also contains a large volume of water, partly stored in the cavities of cells and partly held in absorption. This water significantly affects the behaviour of wood in fire.

3.0 THERMAL PROPERTIES

3.1 THERMAL EXPANSION

Like any other material, wood expands and contracts in response to changes in temperature. The thermal expansion of wood is extremely small. With the exception of very large domed plywood roofs, the heat expansion of wooden structures is negligible.

When wood is heated some of its moisture content evaporates and this causes contraction. This contraction more than compensates for the heat expansion,

3.2 SPECIFIC HEAT

“Specific heat” is the amount of heat energy required to raise the temperature of a unit mass by one degree. In the metric system specific heat is expressed in kilojoule energy per kilogram degree celsius: $\text{kJ}/(\text{kg}^\circ\text{C})$. The specific heat of water is $4.19 \text{ kJ}/(\text{kg}^\circ\text{C})$.

The specific heat of wood varies somewhat, depending on the species and even on individual pieces. For practical purposes, the specific heat of an oven-dry wood specimen is approximately $1.7 \text{ kJ}/(\text{kg}^\circ\text{C})$. In other words, about two and a half-times more heat energy is required to raise the temperature of water than to raise the temperature of wood. The specific heat of wood at 30 percent water content (moisture saturation point) is $2.1 \text{ kJ}/(\text{kg}^\circ\text{C})$.

3.3 EFFECTS OF MOISTURE CONTENT

The moisture content of wood is usually defined as the ratio of the weight of water in the wood to the weight of the oven-dry wood.

The moisture content of trees varies from species to species, and it ranges from 50 percent to 200 percent, or even higher. The moisture content of the sapwood is naturally much higher than that of the heartwood.

Water is present in wood in two forms. There is a large amount stored in the cavities of the woody cells. This water adds weight to the wood and decreases considerably the combustibility of timber. Otherwise it has no effect on the structural properties.

There is also water chemically bonded to the matter of the woody fibre. When the cell walls are completely saturated with “bound” water, the condition is called the “fibre saturation point.” The amount of moisture at this point varies between species and individual trees, but the fibre saturation point of timber, on average, is at 30 percent moisture content.

The moisture content of commercially available lumber is well below 19 percent. This is achieved by artificial drying or by long-time storage.

Wood dimensions will change as the moisture content changes below the fibre saturation point. Wood will shrink as it loses water and swell as it gains water. Shrinkage or swelling across the grain is about 10 times larger than in the longitudinal direction, with the grain.

In the event of fire, water may evaporate very fast from the wood causing warping, splitting or checking which may affect the structural strength of the assembly before the wood is ignited. When wood is exposed to temperatures over 100°C ., the water will boil. The boiling water may stream out in the form of steam, emitting a typical hissing sound. The steam pressure may burst open the wood, causing cracks parallel to the grain, weakening further the soundness of the structure.

The evaporation of moisture consumes a large amount of heat energy, cooling the wood thereby somewhat delaying combustion.

3.4 THERMAL CONDUCTIVITY AND RESISTANCE

Thermal conductivity is a measure of the rate at which heat is conducted through a material. Aluminum conducts heat some 1500 times faster than wood, steel about 350 times, concrete six times and glass four times.

The thermal conductivity of wood depends on the density, water content and the direction of grain. Wood conducts heat two to three times faster parallel to the grain than perpendicular to the grain. Since water conducts heat faster than wood, moist timber conducts heat faster than dry timber.

Thermal resistance is the opposite of thermal conductivity. Actually it expresses the rate at which a material resists the conductance of heat. In the construction industry this resistance is known as “insulating capacity.” When one says that concrete conducts heat six times faster than wood, it means that wood is six times better as an insulating material than concrete. The insulating capacity of wood is about one-third the resistance of glass-wool insulation of the same thickness.

The low conductivity and high resistance of wood is advantageous in some respects; however, it has serious disadvantages as well. For example, if a burning cigarette touches a piece of wood the heat is concentrated in one spot, because it will not be conducted away quickly. As a result, a single cigarette burn can ignite a large section of lumber.

4.0 THERMAL DEGRADATION

4.1 THE PROCESS OF DECOMPOSITION AND BURNING

Wood, as explained above, consists of a series of complex polymers. These polymers do not burn, but at higher temperatures they decompose into three distinct products, which do burn. Thus the burning of wood consists of two phases: pyrolysis and combustion.

The first phase, pyrolysis, involves the decomposition of wood polymers at different temperatures into combustible compounds:

- volatile gases
- tars
- carbonaceous char

This process may commence at temperatures as low as 100°C. The first materials which decompose are the lignins. Since lignins are the glues which hold the woody fibres together the decomposition of lignin will turn the wood into an extremely brittle substance.

If sufficiently concentrated, most of the volatiles can be ignited by relatively low temperatures, sometimes not greater than 210°C.

The second phase, combustion, involves the ignition of combustible compounds by exposure to high temperature or by direct contact with flames.

The volatiles and tars, when ignited, will burn in the form of flames hovering above the surface of solid wood. When these compounds have evaporated, the remaining solid material is more or less pure carbon. This carbonaceous solid, generally called "char," burns without flames in a process which is popularly called "smouldering" or "glowing."

It should be understood that the temperature of a discarded cigarette butt is around 260°. The temperature of an electric arc from a light switch or small thermostat is around 1100°C. The surface of a 100 W light bulb may reach a temperature of 230°C.

Under certain circumstances, around 250°C, slow pyrolytic decomposition may turn into an "exothermic" reaction. Exothermic reactions are chemical processes which generate

high temperatures without outside sources of heat. Frequently exothermic reactions may reach sufficiently high temperatures to cause spontaneous ignition.

So called "thermophile" bacteria can sufficiently elevate the temperature of wood to cause spontaneous ignition. Thermophile bacteria thrive on decomposing wet sawdust or woodchips. They are often the cause of "mysterious" fires if sawdust or woodchips are left in wall cavities after construction is completed.

Tests conducted on wood samples have shown that wood ignites within 40 minutes without the presence of a pilot flame if kept at a temperature of about 205°C. Depending upon the species and the moisture conditions, wood can ignite spontaneously in about five minutes at a temperature range of 320°C to 370°C.

Small pieces of wood will ignite within seconds if touched by the extremely high temperature of naked flames.

4.2 INFLUENCE OF DIMENSIONS ON FIRE DANGER

It is well known that small pieces of wood are ignited more easily than large ones. This is illustrated with the use of kindling to light a fire in a fireplace. The reasons for this are simple. When a larger piece of wood is exposed to flames or high temperature the heat will slowly dissipate along the entire piece. A small piece will quickly reach ignition temperature. Smaller pieces not only heat up to burning temperature faster, they also have relatively large surfaces exposed to the oxygen of the surrounding air.

4.3 CHARRING

When wood is exposed to fire, first the volatiles and tars will burn, leaving the carbonaceous char. This char can be ignited only at much higher temperatures. In effect, char can act as an effective fire insulation on the outside surface of wood.

Scientific experiments have indicated that in a fully developed fire, at temperatures reaching 1600°C, the layer of char will grow at the surface of wood at a rate of 40 mm per hour, or 0.67 mm per minute.

For example, a 50 mm x 100 mm actual dimension lumber, if exposed to fire for 15 minutes, may char 10 mm on all

surfaces, leaving only 30 mm x 80 mm usable cross section. Its section modulus, which is an indicator of the load-bearing capacity, will be reduced by about two-thirds.

A 100 mm x 150 mm actual dimension lumber, if exposed to fire for 15 minutes, is reduced to 80 mm x 130 mm usable cross section. The section modulus of this piece of lumber will be reduced by only one-third.

One 100 mm x 150 mm piece can carry approximately the same load as four separate 50 mm x 100 mm pieces. However, the above example clearly indicates that in structures where fire danger is present, it is advisable to use a few large

section timbers in place of many small dimension pieces. In a fire, the large dimension timber will carry the loads longer, giving a better chance to evacuate the building and initiate fire-fighting procedures.

Codes and engineering manuals provide directions in the use of large dimension wood where fire hazards are prevalent. This type of construction is referred to as "heavy timber construction" and buildings erected according to these principles are called "mill structures." The use of slow-burning construction in mills gained popularity in the mid-19th century with the discounting of insurance rates for mill complexes using heavy timber construction.



Photo courtesy of the City of Ottawa

Fire Damage - The Billings Estate Museum, Ottawa, ON

4.4 EFFECTS OF WOOD TREATMENT

Wood is frequently saturated with fungicides and pesticides to prevent degradation. Furthermore wood is usually treated with sealers, stains, varnishes or paints which serve as preservatives or improve the appearance. While most of these may prolong the useful life of the wood, some of them may increase the fire hazard considerably.

Many preservatives, stains and paint use highly flammable petroleum distillates or other chemicals as solvents. Certain compounds, like resins or gums, which are added to paints or stains are also easily ignitable. The danger presented by these are, in general, twofold:

- certain chemicals burn easily, increasing the flammability of the wood
- some chemicals accelerate the spread of surface flame or generate large amounts of (toxic) smoke, making escape difficult

When considering the use of a preservative treatment or surface coating for wood, the fire hazards should be taken into consideration. In dangerous situations non-flammable, water solvent preservatives or coatings should be used.

5.0 FIRE SAFETY PRECAUTIONS

Though wood is a combustible material it can be used with a considerable margin of safety if adequate precautions are observed.

- a. wood should never be exposed to temperatures over 65°C for extended periods;
- b. wood should never be exposed to open flames;
- c. if heating ducts, steam pipes, or other sources of higher temperatures may unavoidably heat the wood, then provide ventilation to prevent the accumulation of flammable volatiles;
- d. structures built from small sections of timber should be covered with protective sheeting. (gypsumboard, etc.);
- e. avoid saturating or covering wood with flammable preservatives, paints, or other coatings;
- f. if fire danger is foreseen, use large sections of lumber rather than several smaller sections;
- g. always keep the vicinity of wooden structures free from sawdust, woodchips or other flammable construction refuse; and
- h. request the advice of fire protection authorities to develop safe alternatives and trade-offs if codes cannot be exactly followed.

6.0 POST-FIRE ACTIONS

In situations where fire breaks out in a building which contains timber structural elements, the following procedures should be taken after the fire is extinguished:

- a. Examine the structure thoroughly to make sure that no smoldering pieces are left in concealed spaces.
- b. Ensure that all reusable lumber, if soaked by the firefighters, is dried out as soon as possible. It is advisable to apply a water soluble preservative while the wood is still wet.
- c. Remove all wet refuse to prevent the spread of wood-destroying fungi.
- d. Re-evaluate the load bearing capacity of all reusable lumber. Carefully measure the dimensions of the remaining sound wood under the char and re-calculate the section modulus.
- e. Examine all metal nails, fasteners, connectors, etc. Some metals may become brittle, while others may become soft, after a fire. Consider replacing damaged metal fasteners in reusable timber structures.
- f. Ask experts to examine the glue-line in laminated timber elements. Engage a reliable company to inject new adhesives if the glue-line is damaged by the fire.

7.0 BIBLIOGRAPHY

- Butcher, E.G., and A.C. Parnell.** 1983. *Designing for Fire Safety*. John Wiley & Sons, New York.
- Canadian Wood Council.** *Fire Protective Design Datafile*. Ottawa.
- Hall, G.S.** 1968. *Fire Resistance Tests of Laminated Timber Beams*. Timber Association Research Report, WR/RR/1. High Sycombe, UK.
- Harmathy, T.Z.** 1965. "Ten Rules of Fire Endurance Rating," *Fire Technology*, Vol. 1 (May).
- National Research Council of Canada.** 1985. *National Building Code*. Division of Building Research. Ottawa.
- _____. 1986. *National Fire Code of Canada*. National Committee of Fire Code. Ottawa.
- Przetak, L.** 1977. *Standard Details for Fire Resistive Building Construction*. McGraw-Hill, New York.
- Underwriters Laboratories.** 1952. "Report on Fire Hazard Classification of Various Species of Lumber," *Retardant*, Vol. 3365. Chicago.
- _____. 1977. *Fire Resistance Directory with Hourly Ratings for Beams, Columns, Floors, Roofs, Walls and Partitions*. Chicago.
- U.S. Department of Agriculture.** 1974. *Fire Resistance of Wood Construction*. Agriculture Handbook No. 72, Chapter 15. U.S. Forest Products Laboratory, Washington, DC.
- U.S. Department of Housing and Urban Development.** 1980. *Guideline on Fire Rating of Archaic Material*. National Institute of Building Sciences. Washington, DC.
- Wardle, T.M.** 1966. *Notes on the Fire Resistance of Heavy Timber*. Construction Information Series, No. 53. New Zealand Forest Service, Wellington, NZ.

Illustrations are the property of the Heritage Conservation Program, unless otherwise noted.

VOLUME VI

CONSERVATION OF MATERIALS

5.7

WOOD

FIRE PROTECTION TREATMENTS

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: P. STUMES

CONTENTS

1.0 INTRODUCTION

2.0 HISTORIC BACKGROUND

3.0 APPLICATION GUIDELINES

4.0 SURFACE TREATMENTS

4.1 ADVANTAGES AND DISADVANTAGES

4.2 PROPERTIES OF SURFACE TREATMENTS

5.0 IMPREGNATION TREATMENTS

5.1 ADVANTAGES AND DISADVANTAGES

5.2 PROPERTIES OF IMPREGNATION TREATMENTS

6.0 FIRE AND FLAME RETARDANT CHEMICALS

6.1 SURFACE ACTING CHEMICALS

6.2 IMPREGNATION TREATMENTS

7.0 SUPPLIERS

7.1 MEMBERS OF CITW

8.0 BIBLIOGRAPHY

1.0 INTRODUCTION

Wood is an excellent structural material but, at the same time, an easily ignitable substance.

One can reduce the combustibility of the wood itself by using certain chemicals. These chemicals are generally called flame and fire retardants.

Flame and fire retardants serve two purposes: making ignition of the wood much more difficult; and reducing the rate of spread of flame.

It must be clearly understood that these fire protection treatments only reduce the danger of fire; they do not make the wood non-combustible.

Flame and fire retardants are used in three ways:

- a. applied over the surface of wood like a paint or stain;
- b. impregnation of wood by pressure treatment or similar methods; and
- c. incorporated into the material during the manufacturing process. (This method is used when particle boards, plywood or similar materials are manufactured.)

2.0 HISTORIC BACKGROUND

Our ancestors observed that char has some special protective properties. Not only did char resist fungal decay, it was more difficult to ignite. As a result of these observations the first attempt to improve the durability of wood was simply by charring the surface of utensils and structural elements.

Later attempts to improve wood's fire resistance became more sophisticated. The ancient Greeks soaked timber in seawater. The salts which were deposited in the pores, retarded the combustibility.

The Romans soaked the wood of their boats in alum dissolved in vinegar. The wood in buildings was protected in some cases with a coating of clay, lime and loam.

As can be seen, the period methods to improve fire resistance of wood were basically the same as methods used today.

3.0 APPLICATION GUIDELINES

Before considering the application of fire and flame retardants in historical structures, remember that these treatments do not make wood fireproof. Rather, they delay the ignition and slow down the spread of flames, thus allowing a few more minutes to evacuate the building.

Consequently, these methods should be used in spaces where the evacuation of a building is compromised by wood components. Examples of such locations are:

- a. long corridors separated by great distances ;
- b. tall, narrow spaces where fire danger is increased by the chimney effects; and
- c. dormitories with no immediate outdoor exits.

It must be emphasized that those responsible for historic buildings should require adherence to careful housekeeping practices, removal of flammable materials from inside and around the building, and installation of early warning and rapid-acting fire fighting systems.

Fires in historic buildings frequently originate from contemporary displays, textiles and other flammable materials distinct from the building material itself. There are several types of flame retardants on the market which can be applied to paper and textiles.

In some instances it is preferable to close historic buildings to public access rather than destroy the authenticity of the structure with adequate fire protection treatment.

The following are locations where the use of fire and flame retardants are justifiable:

- a. contemporary features which can be ignited easily , especially if the fire may spread to the adjacent historic building;
- b. wood shingles and thatched roofs in high fire risk areas; or
- c. concealed and unsupervised spaces, such as attics and closets, particularly where they contain switches, solenoids, electric motors, thermostats, hot air ducts or hot water or steam pipes.

Fire retardant coatings applied on the surface of wood can be damaged easily and impregnation treatments may leach out

from the wood. Consequently, it is necessary to inspect the treatment at regular intervals.

It must be emphasized that the application of fire and flame retardants requires special skills and equipment. Fire and flame retardants must be applied by companies which are qualified and preferably licenced by the manufacturer of the chemical. Only use chemicals which are approved by Underwriter's Laboratories or by other acceptable institutions.

Where fire and flame retardants must be applied to historic fabric in order to satisfy the authorities having jurisdiction, discuss the application with conservation experts.

4.0 SURFACE TREATMENTS

4.1 ADVANTAGES AND DISADVANTAGES

In historic buildings, the wood is usually built in, either as part of the structure, part of the decoration or part of set-in-place furnishing. The removal of such elements, for treatment in a plant or laboratory, could cause irreparable damage to the authenticity of the building. Consequently, the preferred way to apply fire retardants may be by surface treatment in place.

The main advantages of surface treatment are twofold:

- a. The fire retardants can be applied with the wood in place without disassembling or removing.
- b. Some of the surface-applied fire retardants can be removed from the wood surface, like many paint products. This makes it possible to apply fire retardants as temporary conservation measures. Later these retardants can be removed and longer-term conservation techniques introduced

Not all surface treatments are removable without damaging the surface of the wood and others are not removable at all. Before applying fire retardants as a temporary measure, obtain specifications from the manufacturer. It is also advisable to test the product on a piece of scrap wood before spreading it on the historic fabric.

Surface treatments have many disadvantages as well:

- a. It is very difficult to find fire retardants which resemble historic wood finishes, paints and stains.

- b. Many fire retardants will rapidly degrade if exposed to strong sunlight, humidity, rain, polluted air and other commonly occurring environmental conditions. It may be necessary to test the coatings and repeat the application frequently.
- c. Some fire retardant coatings form a rigid film. When the wood expands or contracts in reaction to moisture, this film cannot follow the changes in dimensions. Such films will break up and flake off the surface of the wood.
- d. Most fire retardant coatings are extremely sensitive to mechanical damage. Some coatings are susceptible to abrasion or scratching even by a fingernail.
- e. Damaged fire retardant coating may give a false sense of security. Assuming that the coating is effective, other fire prevention measures may be neglected or dangerous activities tolerated.

Regardless of the many disadvantages, fire retardant coatings, when applied and maintained properly, can lessen the danger of fire.

4.2 PROPERTIES OF SURFACE TREATMENTS

The most common surface coating fire retardants are applied somewhat like paints or varnishes. The effectiveness of these depends on one or more of the following properties.

- a. **Barrier Action:**
These types of fire retardants cover the surface of the wood with a glaze-like overlay. This membrane is impervious and non-combustible. As long as this membrane is intact and the temperature of the wood under the layer is below the ignition point, the wood is protected from combustion.
- b. **Intumescence:**
Intumescent paints provide an insulating layer around the wood, delaying the build-up of temperature. When exposed to heat, intumescent paints foam up, creating a sponge-like insulation.
- c. **Water Vapour**
Certain flame retardants when heated to 100°C will release water vapour. This phenomenon will persist until all water is released from the paint. Because of the large amount of heat energy consumed to evaporate the water, the accumulation of heat necessary to ignite the wood will be delayed.

d. Combustion Interference

Retardants in this category release gases when heated which retard the flame spread by inhibiting or smothering the flames.

5.0 IMPREGNATION TREATMENTS

5.1 ADVANTAGES AND DISADVANTAGES

Fire retardants can be introduced to wood components by pressure treatment or the steeping method. Particle board, plywood and similar products can be treated by incorporating fire retardant chemicals with the binder during the manufacturing process. Impregnation treatments have many advantages over surface treatments:

- a. Fire retardant properties of the wood are not limited to the surface. Retardant chemicals penetrate deep in to the wood.
- b. Impregnation-treated wood can be used outdoors longer than surface-treated wood. The chemicals used for impregnation will not leach out or decompose as fast.
- c. Impregnation is usually carried out in well-equipped plants by trained specialists ensuring a higher degree of quality control.
- d. In most cases impregnation treatment does not hinder the use of surface adhesives.
- e. Polymerized fire retardants have long-term weather resistance.
- f. It is possible to paint over the surface of many impregnation-treated woods.

Impregnation-treated wood has many undesirable properties which must be taken into consideration:

- a. The chemicals absorbed in the wood can increase its weight by 10-15 percent. This dead load must be taken into consideration when the structural strength of the lumber is calculated.
- b. The wood must be taken into a plant for impregnation. It is rarely acceptable to disassemble an historic structure for this purpose.
- c. The absorbed salts may damage the cutting edge of tools.
- d. Most fire retardant chemicals promote the untimely corrosion of nails, bolts and other metallic fasteners.

e. The heat and moisture applied during treatment can cause warping of the wood.

f. Many chemicals used as fire retardants are hygroscopic; in other words, they attract moisture. Dimensions change as the moisture content of the wood increases or decreases, and the structural strength of wood decreases as the moisture content increases.

5.2 PROPERTIES OF IMPREGNATION TREATMENTS

Impregnation treatments produce their fire retardant effect in one or a combination of the following ways.

- a. Releasing gases:
Certain flame retardants decompose at higher temperatures, releasing gases which inhibit combustion.
- b. Heat absorbents:
Fire retardants may absorb large amounts of heat energy during decomposition, delaying the heating of the wood to ignition temperature.
- c. Reactive agents:
Such chemicals when heated will influence the decomposition of the wood, so as to produce more char and less flammable gases.
- d. Heat barriers:
Some fire retardants adhere to the surface of wood fibres, providing a certain degree of heat insulation.
- e. Chemical bond:
Certain chemicals will bond chemically to the organic polymers of the wood, creating substances with better fire resistance and longer weather resistance.

6.0 FIRE AND FLAME RETARDANT CHEMICALS

There are a large number of chemicals which in one way or another could retard the development of fire or the spread of flames in wood. None of them are perfect and each of them has some kind of negative side effect, such as heavy weight, production of smoke or the emission of dangerous gases.

Fire and flame retardants, aside from the actual retarding chemicals, contain many additives, such as solvents, fixatives, colourings and drying agents. Furthermore, to achieve better results, most commercial products contain a combination of more than one retardant. Manufacturers rarely disclose the exact formula of their products. The list given here contains the most commonly used fire and flame retardant chemicals.

6.1 SURFACE ACTING CHEMICALS

Action	Common chemical
Flame barriers	Sodium silicate
Intumescence	Urea formaldehyde and monoammonium phosphate
Water vapour release	Calcium sulphate
Combustion interference	Antimony oxide

6.2 IMPREGNATION TREATMENTS

Impregnation treatments use one or a combination of the following chemicals: monoammonium phosphate, diammonium phosphate, magnesium chloride or zinc chloride.

7.0 SUPPLIERS

7.1 MEMBERS OF CITW

The following companies are corporate members of the Canadian Institute of Treated Wood and supply fire and flame retardant chemicals. These companies may provide licenced applicators for their products.

The publication of this list does not represent an endorsement, by the publishers, of these companies or their products.

BC Clean Wood Preserves Ltd.
9815 Robson Road
Surrey, BC
V3V 2R9
Tel: (604) 585-2511
Fax: (604) 585-1548

J. A. Biewer (Canada) Ltd.
P.O. Box 967
Cambridge
N1R 5X9
Tel: (519) 621-7701
Fax: (519) 621-0109

Domtar Inc./WPD
395 de Maisonneuve W., 3rd Floor
Montréal, PQ
H3A 1L6
Tel: (514) 848-5324
Fax: (514) 848-5661

Goodfellow Inc.
225, rue Goodfellow
Delson, PQ
J0L 1G0
Tel: (514) 635-6511
Fax: (514) 635-3729

Koppers Industries, Inc.
436 Seventh Avenue
Pittsburgh, PA
15219-1800
Tel: (412) 227-2001
Fax: (412) 227-2889

RAM Forest Products, Inc.
P.O. Box 430
Gormley
L0H 1G0
Tel: (416) 773-1263
Fax: (416) 727-7758

Timber Specialties Ltd.
Box 2, 2nd Line West
Campbellville
L0P 1B0
Tel: (416) 854-2244
Fax: (416) 854-0834

For further information write to:

CANADIAN INSTITUTE OF TREATED WOOD
506-75 Albert Street
Ottawa
K1P 5E7

8.0 BIBLIOGRAPHY

- American Wood Preservers Institute.** 1976. *Comparative Fire Tests of Treated and Untreated Wood*. Serial No. 24679.01. (4840). Factory Mutual Research.
- Bramhall, G. et al.** 1966. *Wood Fire Behavior and Fire Retardant Treatment*. A Review of the Literature. Canadian Wood Council, Ottawa.
- Canadian Wood Council.** 1985. *Fire Protective Design Datafile*. Ottawa.
- Fire Prevention Information and Publication Centre.** n.d. *Flame Retardant Treatments for Wood and its Derivatives*. Fire and the Architect, Fire Prevention Design Guide 13. London.
- Juneja, S.C.** 1973. *Advances in Fire Retardants*. Progress in Fire Retardancy Series, Vol. 3, Part 2. Technomic Publ. Co. Inc., Westport, CT, pp. 31-53.
- Lyons, J.W.** 1970. *The Chemistry and Uses of Fire Retardants*. Wiley-Interscience, New York.
- Rowell, R. M.** ed. 1984. *The Chemistry of Solid Wood*. American Chemical Society, Washington, DC.

VOLUME VI

CONSERVATION OF MATERIALS

6.1

WOODWORK

FINISHING AND WORKING CHARACTERISTICS

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: R. BYRNE

CONTENTS

1.0 INTRODUCTION

2.0 SELECTION OF WOOD

- 2.1 AESTHETIC CONCERNS
- 2.2 APPROPRIATENESS
- 2.3 COST
- 2.4 TECHNOLOGICAL INFLUENCES
- 2.5 PHYSICAL CHARACTERISTICS
- 2.6 SURFACE CHARACTERISTICS
- 2.7 AVAILABILITY

3.0 CONTEMPORARY ANALYSIS

- 3.1 COLOUR
- 3.2 TEXTURE

4.0 CONCLUSION

5.0 BIBLIOGRAPHY

1.0 INTRODUCTION

The conservator of architectural woodwork must understand the craftsman's choice of wood for a decorative purpose and the condition of the existing woodwork.

The conservator should have all the contemporary skills and tools of a craftsman, as well as a knowledge of the social and technological history of woodwork. He or she is not just conserving the fibre of the wood, but is also responsible for preserving the evidence of the history of the object and evidence of the tools that have worked on the wood. Protection of the patina is also a concern. To do this, the conservator must be fully conversant with the use of historic hand tools and techniques; must recognize tool marks and must know how wood develops a patina over time.

Woodwork is not an isolated material. It incorporates many other materials that interact with the wood chemically, mechanically and environmentally. The conservator must be aware of the nature of the materials he or she is working with. It is possible to strip the dark varnish from what is thought to be a Victorian carving, only to find that it is made of plaster or compressed sawdust and glue. The use of a water-based paint remover on such a carving could destroy it.

Today a variety of new materials are being incorporated into "woodwork," such as plastic varnishes, cast plastic foams, vinyl-clad wood and others. In the future, these will require closer examination by conservators who will require a wide scientific background in order to deal with the problems that these materials will present as they deteriorate.

The conservator must work with the materials chosen by the craftsman even if he or she knows that original use of a different material would have avoided problems. The conservator must apply corrective measures, based on an understanding of what went wrong and how the problem should be dealt with.

2.0 SELECTION OF WOOD

2.1 AESTHETIC CONCERNS

One of the factors that affect a craftsman's choice of wood is its aesthetic quality. This includes:

- a. the colour, both in its wet and dry state (i.e. with and without a clear finish);

- b. the grains, including how well they blend into existing woodwork; and
- c. the translucent lustre and depth found in some woods (e.g. tiger striped maple).



Porch Detailing

2.2 APPROPRIATENESS

The degree of exactness or "finished state" that is expected of the object is another factor. One does not expect the same care in construction of a barn or a log house as one does in a church. Each has its own sense of being "finished." The choice of materials and the way they are used will contribute to this.

This sense of being "finished" is often the result of fashion and personal taste. For example, historically, oak floors were often laid in parlours because it was thought to be more tasteful or fashionable than maple which was used in the kitchen or pine used for bedroom floors.

2.3 COST

Cost is another factor, involving both the cost of the raw wood and the cost of working it into something useful. Cost must be

regarded in light of supply and demand which in turn means understanding the development of trade patterns for imported finished lumber and the interruptions this trade may have suffered due to major events. Any of these might have affected the availability of a given species. "Imported" means any wood that is transported from one locale to be used at another.

2.4 TECHNOLOGICAL INFLUENCES

Supply and demand has been greatly affected by the development of modern machine technology since the end of the 18th century, which allowed for mass production and major shifts in marketing methods. Catalogues from the end of the 19th century indicate how abundant goods and styles had become. Modern machines made it possible to manufacture goods more cheaply and made it possible to use some woods that could not be worked with hand tools. To be useful to someone pushing a moulding plane, wood must be straight-grained and free of knots. This is not the case with high-speed cutters used on wood-shaping machines as these cutters are capable of cutting a great deal of wood with irregular grain patterns. "Goods" once milled, must be marketed and transported to the job site. Hence, knowledge of when certain tools were introduced into the wood-working industry is not enough. One must learn about a particular locality and its market development.

2.5 PHYSICAL CHARACTERISTICS

Softwoods such as pine are very easy to cut, and accept a variety of colours well. But pine will not stand up to constant wear and abrasion. Thus, where wear and tear could be a problem, such as in chair rails, a craftsperson might use a harder wood such as oak. Density of wood can be important to selection if fine carving has to be incorporated into the design. The dense wood fibres will hold detail better, not only when cut, but more importantly under conditions of stress and wear.

2.6 SURFACE CHARACTERISTICS

When selecting lumber, the woodworker must take into account those characteristics of wood that affect the way light reflects from it. Oak and mahogany have long open grain pores which diffuse light. To increase the gloss achieved with varnish, the worker will fill these pores with a fine, inert filler. The conservator must be aware that such fillers might be present and insure that the restoration process leaves the fillers intact or at least replaces them during the refinishing process.

Another aspect that affects the way light reflects from a wood surface is the sheen that may be left behind by sharp cutting tools. Sculptors can spot the difference between wood that has been air dried or wood that has been kiln dried. The kiln drying process tends to bake the oils and resins in woods and hence the quality of the sheen or patina that is left behind is different.

The current trend to sand most woodwork before it is put in place is partly the result of the availability of modern cheap sanding papers. Woodworkers have often relied on planes and scrapers to create a glass-smooth surface. This surface is slightly different from the surface left behind by the many fine cutting edges of sandpaper, regardless of how fine the sandpaper is.

In a historic building, one often observes the results of shrinkage, such as the cracks between floor boards and the deep line shadows that result. Evidence of shrinkage is also found in wainscoting. These shadow lines form an important element in the appearance of the finish in a structure.

Kiln-drying of timber on a large commercial scale is a relatively recent development. Alone, kiln-drying provides no guarantee that shrinkage or expansion will not occur because this can happen during subsequent climatic change. The performance of kiln-dried lumber depends on the manner in which the wood is protected from the environment during shipment, and whether it is allowed to reach the equilibrium moisture content of the room in which it will be used before installation.

The architectural conservator has to judge the suitability of modern materials as replacement stock in terms of their ability to match the same shrinkage patterns as the original. This may be very difficult to do, considering that the kiln-dried lumber of today suffers from inadequate transportation and storage conditions. Most jobs are further complicated by tight schedules. As well, wood is seldom allowed to adjust to the moisture conditions of the place it is destined to be installed. Shrinkage, either desired or undesired, must be carefully considered if a structure is to be maintained as it was found.

2.7 AVAILABILITY

Today the craftsperson's selection of lumber is restricted compared to earlier times when virgin timber stands were abundant. Virgin timber offered board widths and lengths that are not commonly available today. Grain and wood density is frequently different in virgin timber from the wood of

second and third growth, due in part to the difference in spacing between the trees. With less access today to large diameter trees, boards are more likely to be plain-sawn (tangentially sawn) rather than quarter-sawn, affecting both their appearance and their stability.

Along with the demise of virgin timber there is a relative scarcity of many species because they have not been replanted or they have an extremely long maturity cycle. Also, woods of the same species, but from different locales, can vary in appearance considerably. For example, the colouration in woods such as walnut or cherry varies depending on where they were cut and the trace elements that were present in the soil. Some woods may no longer be available in certain widths and lengths at any price.

Second-hand lumber salvaged from other structures and from furniture might be available. This type of material has a variety of advantages and problems when used in restoring woodwork:

Advantages:

- a. it may give the same basic grain as existing woodwork eg. grain in quarter-sawn oak; or
- b. it may give the same patina as existing woodwork, e.g. colour change between old and new cherry.

Disadvantages:

- a. there may be old nails to damage tools as the wood is reworked;
- b. used timber may have holes from nails and joint work, which might have to be repaired;
- c. used timber has a greater chance of being infected with wood-destroying insects and fungi, which may affect the rest of the structure;
- d. the oils and resins in old lumber may have dried, and hence the wood will work differently from new stock. Frequently, shavings will be brittle because the wood fibre does not cut as cleanly. Some woods such as 200-year-old cherry may take on a sugary texture when reworked. This texture will greatly affect the way light plays on the surface; and
- e. the colouration of old wood can be very different from new wood. Where fresh cuts are made in old wood, the resultant colour change will vary over time, compared with new wood.

None of the above factors are conclusive reasons to either use or avoid using reclaimed lumber. Frequently old wood is sought out simply because it is old, and thus assumed to be more appropriate for repair work. This is to be discouraged when potentially valuable woodwork must be destroyed or dismantled in the process.

3.0 CONTEMPORARY ANALYSIS

The key to woodwork conservation is observation of materials and how they interact. The conservator will have to consider the concerns of the original craftsman. The conservator must decide what the finished woodwork is to look like, taking into account colour, gloss, texture, shrinkage and patina.

3.1 COLOUR

Colour is perceived differently in different lights, and in wood exposed over time to light and air. Hence the job of reporting a colour is a very difficult one (see Vol. III.9.2). The oils and binders that make up most finishing materials also change colour over time. Waxes, oils and dirt build up on woodwork altering colours. As finishes crack with age, the way light reflects off them and their perceived colour will change (see also Vol. VII.12.3).

Often the colour seen is the result of a chemical change caused by the craftsman during the finishing process. Oak can be fumed with ammonia to turn it varying shades of gray. Mahogany can be enriched with permanganate of potash. The colour change in the wood may be due to the use of a dye material that was placed there with water or alcohol and hence care will have to be taken not to lift these stains during examination or refinishing. The colouration that one sees may be nothing more than a pigment in a binder that has been brushed on. Understanding a finish colour is not an exact science, but rather an exercise in judgment based on several variables. One must remember that often judgment is clouded by preconceived notions.

3.2 TEXTURE

The conservator must observe the texture of the wood and devise methods to ensure that during the restoration process this texture is not destroyed by raising the grains with paint removers, sanding or scraping. One must be aware of tool

marks left by planes and hammers. The conservator must look for differential shrinkage across different grain densities (in some woods such as fir) that cause a smooth wood surface to take on a rippled effect. Additives, such as fillers, that have been used to change the native raw texture of the wood is an additional concern.

4.0 CONCLUSION

The architectural conservator often has a considerable task. Whereas a painting conservator may only have to deal with a small area of canvas, the architectural conservator is often faced with many square metres of woodwork which makes up a major part of the ambience of a historic structure. Each square metre should be conserved intact as far as budgets allow.

5.0 BIBLIOGRAPHY

- Blackie and Sons.** 1970. *The Victorian Cabinet-Maker's Assistant*. Reprint of 1853 edition. Dover Publications, Inc., New York.
- Cescinsky, Herbert.** 1967. *The Gentle Art of Faking Furniture*. Dover Publications Inc., New York.
- Fleming, Stuart J.** 1975. *Authenticity in Art*. Crane, Russack and Co., New York.
- Hayward, Charles H.** 1970. *Antique or Fake*. Evans Brother Limited, London.
- Peterson, Harold L.** 1975. *How Do You Know It's Old?* Charles Scribner & Sons, New York.
- Pey, David.** 1971. *The Nature and Art of Workmanship*. Van Nostrand Reinhold Company, New York.
- Roubo, J.A.** 1977. *L'Art du Menuisier*. Leonce Laget, Paris. Reprint of the 1769 edition, which is probably the most extensive work ever written on woodworking.

Illustrations are the property of the Heritage Conservation Program, unless otherwise noted.

VOLUME VI

CONSERVATION OF MATERIALS

6.2

WOODWORK

DETERIORATION AND DEFECTS

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: R. BYRNE

CONTENTS

1.0 INTRODUCTION

2.0 SHRINKAGE

2.1 JOINTS

2.2 PANELS

2.3 TURNED WORK

2.4 HARDWARE

2.5 CHOICE OF MATERIALS

3.0 LOOSENING OF JOINTS

4.0 WEAR

5.0 SUNLIGHT

6.0 HUMIDITY AND TEMPERATURE

7.0 SITE DEVELOPMENT ACTIVITY

8.0 BIBLIOGRAPHY

1.0 INTRODUCTION

This article describes the changes that occur to architectural woodwork during the passage of time (physical abuse, wear and tear, development of patina) or changes due to characteristics of the wood inherent in its make-up (knots, shakes, shrinkage characteristics). The distinction between deterioration and aging often depends on the aesthetic perception of the observer. Aesthetics can become extremely important in the consideration of a proposed conservation treatment. Hasty conservation decisions made by the insensitive and unskilled worker can alter for generations the nature of an artifact.



Wood Damage at Door Hinge and Frame Joint

2.0 SHRINKAGE

Wood shrinkage is an important change that occurs to decorative woodwork. Selection of a species with inappropriate shrinkage characteristics and improper drying will affect the overall performance and fit of any woodwork.

2.1 JOINTS

The nature of a mitre joint is such that shrinkage across the grain of the two pieces mitred together will cause the joint to open over time. This can often be observed at the corners of ancient picture frames or in case mouldings around windows and doors. Correction of this fault requires dismantling and recutting the mitre, but it would also shorten the length of the members and might damage the woodwork during dismantling. Refitting the mitre also causes the loss of some evidence of the structure's age.

Because most woods undergo negligible longitudinal shrinkage, butt joints show the effects of shrinkage in one member only across the piece butted. The total opening of the joint, however, will be far less than with the mitred joint. The mechanical means of holding the joint together, whether nails, mortise and tenon, spline, etc., is also a factor in determining how far the joint opens. Joining techniques determine how a joint "works" or moves, that is, how easy it is for a joint to move in response to constant expansion and contraction caused by changes in the relative humidity in a room.

Another subtle change caused by shrinkage of woodwork, is that mortise and tenon joints that are pinned together will often have the pin or peg projecting beyond the surrounding wood. This is the result of differential shrinkage. The wood in the joint shrinks across the grain while the length of the peg shrinks very little. Unskilled or unknowing workers often pare these peg ends flush again, which can significantly reduce the value of the piece, because a major indicator of its age has been lost.

Frequently the corners of veneered boxes and dressers are dovetailed together. One can feel a hump under the veneer where differential shrinkage has taken place. At times the shrinkage is so great, and the glue so brittle, that the veneer lifts off. If the veneer is to be replaced, the conservator will have to cut the dovetail flush again. However, this will destroy part of the piece's authenticity. It is in such cases that the judgment of an experienced conservator is needed.

2.2 PANELS

Shrinkage also affects the fit of panels in doors and other house woodwork. These units were built as panels to overcome the effects of shrinkage over wide areas of wood. Panels in doors are designed to expand and contract in the rabbets in which they are placed. It is only when the necessary movement of the panels is restrained that damage results. If a panel does not have free movement in its rabbets, it will crack parallel to the grain with the first change of season and the resultant change of relative humidity. Panels which are held firmly in place by heavy layers of paint are also unable to move freely and soon crack. The same damage results when a panel is glued in place or repaired with brads placed through the rabbet and panel to "hold" the panel in place. Hence great care must be exercised by painters and by joiners who may disassemble and reglue the woodwork.

Avoid painting panels in their "swollen" position, because shrinkage will cause the paint film to crack and expose an edge of unpainted wood that will show as the wood dries and shrinks. This can be as much as a quarter of an inch on each side of a panel on a newly installed door.

Bolection mouldings on panels pose a problem as panel movement occurs. If the bolection moulding is "frozen" to the panel either through construction error such as use of brads or because of accumulated paint, the resulting panel movement will cause the bolection moulding to pull away from the stile and become warped. The bolection moulding must be fastened to the rail and stile but must not be painted to the panel.

2.3 TURNED WORK

Shrinkage is often the definitive test of age. This is also true of woodwork turned on a lathe. Shrinkage will cause newel posts to become slightly oval as opposed to round, the shape they had when they came off the lathe. This can be checked very easily with a pair of calipers laid across the newel post's two axes.

2.4 HARDWARE

When wood is freshly cut and installed, it will start to pinch down on the edges of hardware such as hinges and lock plates that have been recessed to make them flush with the surface of the wood. This causes the fit of the hardware in the wood to become very tight over a few years time. The addition of several layers of paint also helps to bind the hardware in

place. Attempting to remove the hardware for repair may cause the tight edges to remove large splinters of wood with it. This can be avoided by first ensuring that the paint and binding wood are cut free around the edge of the hardware.

2.5 CHOICE OF MATERIALS

Wood shrinkage also results from selecting the wrong wood or using wood with the wrong cut of grain. One might see softwood floor boards where partial or complete delamination between summer and spring growth of the wood has occurred. This condition is aggravated by constant wear. This same condition may be seen in softwood wainscoting, shutters exposed to severe weathering, etc.

Such shrinkage problems can only be avoided through selection of the proper species that have been cut and seasoned to suit the task at hand. This must be followed by proper joint design and long term stable environmental conditions.

At times, fine woodwork fails because of the nature of the wood itself. This can be seen, for example, in expensive rosewood furniture whose joints never seem to stay glued. The oils in rosewood form poor bonding surfaces for glue. Over time these oils harden, leaving a joint almost impossible to reglue. This condition is usually limited to fine tropical woods.

3.0 LOOSENING OF JOINTS

Shrinkage at the base of a stair spindle may result in the spindle no longer fitting snugly into its mortise or dovetail and rattling each time the stair rail is shaken. Once a joint is loosened, constant use and movement will quickly aggravate the condition. Joints also loosen because of embrittlement of the glue holding the joint together. Nails, pegs and screws used to fasten joints can work loose, leaving the joint free. The result of this joint movement is commonly seen at the joint line where rail and stiles are matched together. The movement will appear as a ragged crack in the embrittled paint film.

Wood constantly moves. There is little that can be done, with the exception of controlling the relative humidity of the surrounding environment. The real danger to historic woodwork lies in the actions of unskilled workers who think they can stop the movement with nails and braces, followed by even more nails and braces, until the object has torn itself apart.

4.0 WEAR

Deterioration of woodwork, and the resultant patina and ambience it gives a structure, is often a problem for the conservator. People come to historic sites with the expectation of seeing the "original." It is often necessary to replace a wood door threshold, yet maintain the feel that thousands of feet have worn away the wood.

The durability and the nature of the deterioration of many woods must be considered when developing the traffic flow patterns in a historic structure. For example, a floor might exhibit a gentle flow of ripples as soft wood has been worn away while the harder knots have remained intact, or nails may have withstood wear better than the surrounding wood and may project above it. All of this is important to the visual "feel" of historic woodwork. Often woodwork is abused by architects bent on "restoring" a structure to some preconceived idea of primeness. No rules can be set, other than recognizing the need to be aware of the irreversible changes to structures as time-worn wood is discarded. Public safety must be considered, but so must the integrity of the artifact. The wear of historic materials can be reduced by limiting group size or by using mats, cat walks, duck boards, etc. Protective shields and barriers can also reduce the wear on decorative finishes that the public otherwise might reach out and touch. The architectural conservator plays an important role in the design of interpretive programs. Preventive conservation is by far the most effective conservation.

5.0 SUNLIGHT

Because light plays an important role in the deterioration of wood and its finishes, the conservator must assist in determining the types and amounts of light that are to be present in a historic structure. Intense sunlight falling on an object can raise its surface temperature significantly and, in so doing, greatly speed up the deterioration of oils and other finish elements. The ultraviolet rays present in sunlight (and from other sources) will break down many finishes and organic materials. Strong sunlight can change the colour of many pigments found in wood and finishes. Ultraviolet (UV) filters and blinds will reduce the amount of light in a room and retard the damage caused by light. UV filters can be fitted into a window design with little trouble and filter tubes can be fitted over fluorescent light tubes.

6.0 HUMIDITY AND TEMPERATURE

Variations in humidity cause expansion and contraction of wood. In so doing, joints are forced open as previously described and decorative finishes may be ripped free of the wood supporting them. Gesso layers holding gold leaf may be broken into small pieces and paints may crack because they are unable to follow the movement of the wood fibres below. Humidity changes are often accompanied by wide ranges of temperature, particularly in historic buildings that are closed to the public during winter. High temperatures may cause finishes to "bake" and craze, while low temperatures accompanied by moisture condensation may cause a white "blossoming" to appear on a finish. Excessive surface moisture may also encourage fungal growth.

7.0 SITE DEVELOPMENT ACTIVITY

Historic woodwork and finishes also experience mechanically caused changes. The restoration process is often the most significant intervention a structure will ever undergo. It is often much more damaging than the wear and tear of normal usage. Too often, no thought is given to whether the intervention can be repaired or done in such a way as to leave no scar.

For a structure to retain evidence of its historical record, it must be approached with extreme care. Workmen must be instructed to care for woodwork as if it were fine furniture. Often woodwork is removed and stored as if it were common cordwood. Doors are removed from their hinges and piled one on the other with little thought to the damage being done by the door knob digging into the door behind. Pry-bars are used to pull casings loose, only to leave ugly scars where the bar has dug in. Windows that won't open are pried open with screwdrivers which leave ugly scars behind. Nails are dropped on floors and walked on, grinding the head deep into the wood. Nails are driven into woodwork for use as hangers for workers caps, tools or temporary wiring. Each of these careless actions are completely avoidable if everyone on the job site realizes that each blemish inflicted during the active restoration process is a blemish that must be repaired. Many of these scars are irreparable and will remain with the structure forever. Too often the original structure is considered just a model for the replacement materials.

Economic considerations always play an important role in architectural conservation, but economics should never be blamed when the real reason is lack of concern for safeguarding the original material.



St. Andrew's Manse, Dawson, YT

8.0 BIBLIOGRAPHY

- Anon.** 1970. "Studies in Conservation," *The Journal of the International Institute for Conservation of Historic and Artistic Works*, Vol. 15, No. 4 (November). London.
- Feller, Robert L. et. al.** 1959. *On Picture Varnishes and Their Solvents*. The Press of Case Western Reserve University, Cleveland.
- Gettens, Rutherford J., and George L. Stout.** 1966. *The Artist's Handbook of Materials and Techniques*. The Viking Press, New York.
- Thomson, Gary.** 1978. *The Museum Environment*. Butterworths, London.
- Torraca, Giorgio.** n.d. *Solubility and Solvents for Conservation Problems*. International Centre for the Study of Preservation and Restoration of Cultural Property, Rome.

Illustrations are the property of the Heritage Conservation Program, unless otherwise noted.

VOLUME VI

CONSERVATION OF MATERIALS

6.3

WOODWORK

CONSOLIDATION AND REPAIR

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: R. BYRNE

CONTENTS

1.0 INTRODUCTION

2.0 CLEANING

3.0 REPAIR

3.1 LENGTHENING DOORS

3.2 REPAIRING CRACKED PANELS IN DOORS
OF RAIL AND STILE CONSTRUCTION

3.3 FILLING SMALL HOLES

4.0 CONSOLIDATION

5.0 REMOVAL OF HARDWARE FROM
WOODWORK

6.0 BIBLIOGRAPHY

1.0 INTRODUCTION

The best conservation is preventive conservation. Control of the two major sources of damage, human and climatic, will do the most to prevent damage to interior woodwork.

Human-inflicted damage comes from visitors and from careless site restoration personnel. Remember that it is not just wood that is being worked with, but a mixture of nails, screws, varnish, waxes, paints, gold leaf, gesso, etc. Poor work habits, poor choice of repair and maintenance materials or ignorance of repair techniques are all sources of damage to historic woodwork during restoration.

Consider the complexity of woodwork when planning a program of cleaning, consolidation and repair. A few basic principles should be kept in mind. Remember why the action is being taken. Too often, action is taken just because it is possible to do it. For example, paint is sometimes stripped away to reveal the "beauty" of the wood below, or harsh detergents are applied to paint to make it look clean and new. The temptation exists to bring an object back to its "new" condition, but in so doing, the basic law of conservation, that of minimal intervention, is violated.

Historic woodwork is often overlooked, abused or discarded during building restoration if the restorers do not know how to go about preserving it.

This article's purpose is to save such material from unwarranted destruction by providing architects and craftspeople with a guide to its restoration.

2.0 CLEANING

There are several ways to clean woodwork. Methods include mechanical means such as scraping or sanding, washing with soap or detergent (washing will remove some finishes) or the use of solvents, which can dissolve oils, waxes and finishes.

Cleaning materials can present serious health hazards. Scraping and sanding of lead-based paint can cause lead poisoning if the dust is inhaled. Some solvents can be absorbed through the skin or inhaled, resulting in accidental "drunkenness," tissue and organ damage and headaches. Benzene, common in some paint removers, can cause a type of cancer, while methylene chloride, often found in other types of paint removers, can trigger heart attacks in people with heart conditions.

Caustic paint removers work because their caustic action softens the oil binders, allowing the finish to be removed with a scraper. Trisodium phosphate, lye and other strong caustics are used as paint removers or as strong cleaning agents. These can cause severe chemical burns and if they contact the eyes, blindness may result. It is extremely important to be fully informed beforehand of health hazards and to establish an effective set of measures and equipment to ensure that the work is done safely.

Strong soaps and detergents present another problem. Many cleaning agents, once applied to woodwork, leave behind residues that are only noticeable over time. Paint scrubbed with harsh detergents may decay very rapidly after being "cleaned," because the alkali in the detergent may have destroyed the bonding agents in the finish. Paint remover residues must be carefully removed or neutralized when used on wood.

Caustic soda left on bare wood after paint stripping will destroy any future layers of paint that may be applied. Methods that may seem cheap and easy to use may in fact damage the woodwork.

Another important rule to consider when choosing a solvent or cleaning agent is its ability to be controlled, i.e., whether it does what is intended, and no more. For example, it may be necessary to remove a layer of yellowed shellac without touching the fake graining underneath. A solvent must be chosen that is capable of doing this.

Architectural conservators face a set of problems that other conservators do not when they choose materials: the materials must be cost-effective and able to be used by relatively unskilled workers. Always carefully test proposed treatments with these thoughts in mind before specifying full-scale operations.

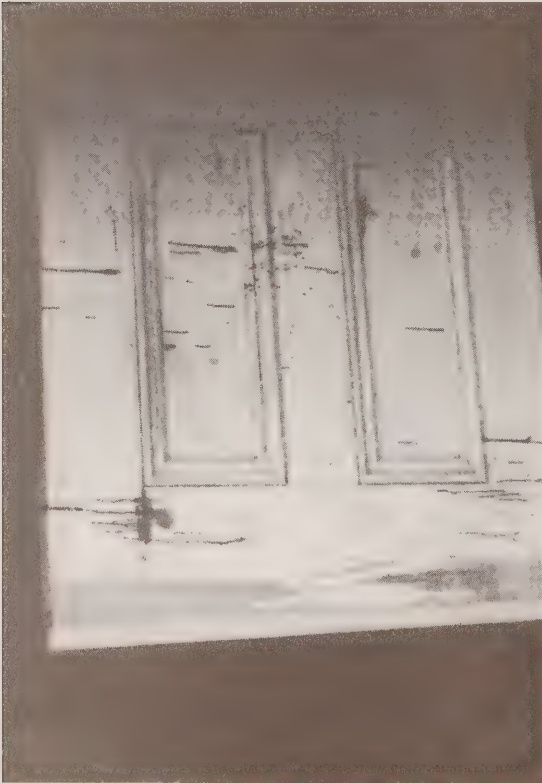
3.0 REPAIR

Perhaps the best experience in woodwork conservation can be obtained through the restoration of furniture, as the techniques used in this craft are directly transferable to fine woodwork restoration. To explain woodwork repair techniques, it will be helpful to provide typical examples of repair procedures.

3.1 LENGTHENING DOORS

When lengthening a door, it is not difficult to glue a piece of wood in place at the bottom. The difficulty is keeping the added piece in place, because the butt ends of the stiles will not shrink to the same degree as the rail. Consequently, the added wood will be forced free of the rail as the rail shrinks.

Also, the glue joints, which are weak due to their location on the stile ends, will break if the rail expands. Give the joint additional support by running a 6.35 mm spline the full width of the door. If the spline is made from plywood, it will resist cracking out. Solid wood splines can be used if they are cut so that the grain of the spline is 90 degrees out of phase with the grain of the door.



Detail Showing Lengthening of Door.

3.2 REPAIRING CRACKED PANELS IN DOORS OF RAIL AND STILE CONSTRUCTION

Usually, the only way to repair a cracked panel is to dismantle the door, remove the panel, clean the crack, refit it and then glue the door back together. Trying to repair cracked panels in place normally does not work because the fit of the crack will be bad and the crack may be full of foreign matter. It is important to keep the panel moving freely in its grooves. Do not fill the dado crack with wood putty or other filler, which will cause the crack to force its way open even wider.

3.3 FILLING SMALL HOLES

There are a variety of ways to fill small nail holes, nicks and dents in woodwork. The most common material used during the 18th and 19th centuries was a mixture of chalk, linseed oil, egg white and sometimes a little white lead. Another early plugging material was sawdust bound up with hide glue. Wax and shellac were also used.

A wide range of fillers are available today besides these historic materials. Plastic woods with acetone thinners are common but unfortunately they shrink as they dry and do not absorb stain. Most cellulose fibre filler will take stain to a degree, but be sure the filler will not dissolve when a particular finish is applied over it or that it will not shrink below the surface of the wood as it dries. Wax and shellac sticks come in many different colours and are used for the same purpose as fillers. The sticks are melted into place, left to dry and rubbed off or sanded smooth. If these fillers do not absorb stain, the restorer may use coloured tints. These can be brushed or sprayed on over the filled area.

Since wood changes colour over time, it is often necessary to foresee the final expected colour and use a filler darker than the newly finished wood. The new epoxy fillers designed for wood repair can be extremely useful as they do not shrink and will take dry colours while in a soft putty state.

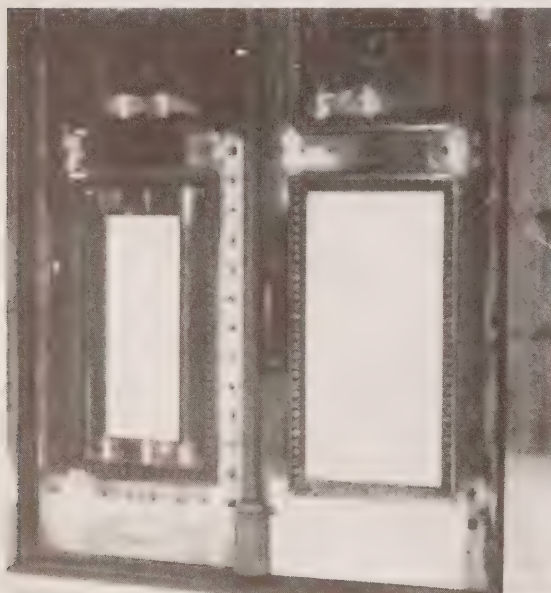
Small indentations may be reversed by applying steam to the bruised area. This is not always successful, as wood fibres, once crushed, often remain so and steam may not be able to again bring the bruise fully flush with the surface.

Plugs are often used to repair small holes. Plugs are cut from a piece similar in grain to the piece being restored. A hole, the exact size of the plug, is drilled into the place needing repair. The plug is glued into this hole with the grain lined up with that of the piece being repaired. If carefully done, it is possible to achieve very good results, with only the glue line showing.

Avoid using dowelling as the grain goes in the wrong direction. A plug will shrink in the same plane as the repaired piece, while a dowel shrinks at right angles. Consequently, the dowel eventually will project beyond the face. Also, the end grain of the dowel will absorb stain differently from the surrounding wood and will absorb a finish more readily, creating problems if the piece is to have a clear finish.

A peg works as a fixing device because it is an irregular polygon forced into a round hole. As it is driven into the hole, the peg cuts its own channel and locks itself in place. When joints that have been pegged together are taken apart, record each peg, the hole it came from and the orientation it had to the hole itself. If not, damage will be done when the pegs are replaced. Dowels are often used to peg joints together. Avoid their use.

Wood fillers are not strong enough to bridge sizeable gaps. Use the wood plug technique to fill large holes in solid wood. It is easiest to define the hole with pencil on a piece of paper held in place over the hole. This then becomes a pattern against which to cut an odd-shaped wood plug inlay. An odd shape is preferred as it will blend better into the surrounding grain.



Door Patching

The restorer can also use autobody filler to close sizeable gaps. To use this technique the person must know and be able to apply the grain simulating technique.

Several problems are encountered when plugging holes in doors that were bored to insert modern tumbler locks. Generally, round plugs are used to fill the holes. When such plugs dry, they shrink, and leave very clear circles. Often, the shrinkage is enough for the plugs to work loose.

It is bad practice to repair cracks with nails or screws. For example, should the nose of a stair tread crack and pull away, nailing will not hold up to the stress. Glueing and clamping is necessary.

Long, tapering scarf joints are useful when the ends of mouldings are broken or missing or when an inch or so of wood must be added to a moulding. With the new wood scarfed in place, it is easy to recarve the moulding to the proper profile. Such repairs, when done well, are almost impossible to detect, either on painted or clear-finished work.

4.0 CONSOLIDATION

Another group of repairs falls under the heading of consolidation. When wood has been severely attacked by insects or fungus, there is often little structural wood left, leaving the piece incapable of supporting the slightest loads or pressures.

Make the decision to consolidate a wooden member with caution, especially if the repaired member must bear weight, for most consolidation procedures will not give a structural member the same strength it once had.

Decorative trim woodwork, in large measure, is not structural and hence can be consolidated without its load-bearing qualities being an important factor.

Before selecting a consolidation technique, consider the purpose. Consolidation should be done only in those cases where the decorative or historic value, or replacement cost, are major considerations and where leaving the piece unconsolidated might lead to its collapse.

Most consolidation techniques are best accomplished in a laboratory, rather than on a construction site.

Waxes are the oldest historic materials used in consolidation of deteriorated wood. The problem with wax, as with any consolidant, is getting it into the wood. Gravity feed is difficult, as molten wax will cool before entering the wood. Hence, hot wax baths are required to get the wax in place; these are expensive and limited in their application.

Modern products such as *Xylamon* from Germany are also wax-like in their consolidative effects. *Xylamon's* advantage is that it remains in a liquid state until it has entered the wood, where it then solidifies. Paint does not adhere well to surfaces coated with waxes; likewise, *Xylamon* produces a surface that is also difficult to paint. Little real strength is added to the wood, but the fibres are now bound in place.

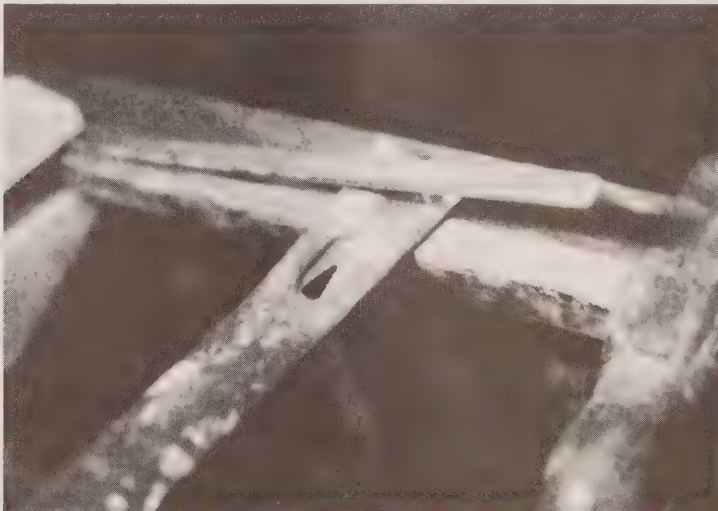
More durable consolidants are available in the form of liquid epoxies which can be blended into a variety of densities and viscosities, and which, when hardened, have various degrees of elasticity. Filler additives are available to vary colour, texture and weight. These types of epoxies have long been used on small wooden boats. Some available epoxies are like paste fillers, while others are liquid and diffuse well into the wood's fibres.

Consolidation work can, at times, be strengthened using dowels placed lengthwise to the work. Drill long holes into the end of the piece and glue the dowels in place. This technique can be used very successfully to strengthen the legs of furniture, stair spindles, etc.

5.0 REMOVAL OF HARDWARE FROM WOODWORK

Shrinking wood and layers of paint tend to bind tightly to hardware that has been let into the surface of the wood. Careful cutting around the edge of the hardware is usually sufficient to break the seal so that the hardware can be removed with little damage to the woodwork.

Screws can be very difficult to remove. Always clean the head of the screw so that it is free of paint binding it to the hardware or wood. Then clean the slot so the screwdriver fits as well as possible. Use a screwdriver that is the width and thickness of the slot. Often, there is only one chance to remove an old screw before the head slot rounds over, making removal impossible. It



Proper Use of A Pry Bar

is worth the effort to take as many precautions as possible to make the screw come out on the first try. If the screw is rusted in place and will not move, use the tip of a soldering iron to apply heat, which may free the screw.

If the screws are handmade, keep them separated and numbered with identification tags to ensure their return to the holes they came from, as each will have its own unique thread. It is a good practice to have small bags for the hardware and screws as they come off the woodwork.

When woodwork is removed from a room, it is often necessary to remove nails that have been set below the surface of the wood. If these nails are driven back and removed the way they were driven in, severe damage usually results as the hard fillers and the shrunken wood around the nail cause large splinters to break out. It is better to clip the nails flush on the back side of the woodwork or to pull them completely through from the back.

A quick response is often important in woodwork conservation. Make certain that little pieces, knocked free from wood, are glued back immediately and not an hour later. Waiting could result in loss of the piece, or damage to the edges that were to be glued together, making a clean glue job impossible.

Develop a system to identify wood as it is removed from a building. Hobby wood-burning kits are ideal for branding a code number on the back of woodwork. Steel stamps with letters and numbers or even pencil crayons can also be used. The chosen system should be waterproof and not easily obliterated with dirt.

6.0 BIBLIOGRAPHY

Alcouffe, Daniel. 1977. *The Restorer's Handbook of Furniture*. English translation of the French edition. Van Nostrand Reinhold Company, New York.

Dresser, Christopher. 1977. *The Art of Decorative Design*. Reprint of the 1862 edition. American Life Foundation, Watkins Glen.

Hallett, Charles. 1952. *Furniture Decoration Made Easy*. Charles T. Branford Co., Boston.

Hayward, Charles H. 1969. *Staining and Polishing*. Drake Publishers Inc., New York.

_____. 1977. *Antique Furniture Repair*. Coles Publishing Company Limited, Toronto.
This is by one of the world's most knowledgeable cabinetmakers.

Lipman, Jean. 1951. *American Folk Decoration*. Dover Publications Inc., New York.

Marsh, Morton. 1959. *The Easy Expert in Collecting and Restoring American Antiques*. J.B. Lippincott Co., New York.
The title is misleading – this is one of the best books ever printed on furniture restoration.

Miller, Margaret M., and Sigmund Aarseth. 1974. *Norwegian Rosemaling*. Charles Scribner & Sons, New York.

Rodd, John. 1976. *Repairing and Restoring Antique Furniture*. Van Nostrand Reinhold Company, New York.

Waring, Janet. 1968. *Early American Stencils*. Dover Publications Inc., New York.

Wenn, Leslie. 1975. *Restoring Antique Furniture*. Barrie and Jenkins Ltd., London.

Wright, Florence E. n.d. *How to Stencil Chairs*. Penn Yan, New York.

Illustrations are the property of the Heritage Conservation Program, unless otherwise noted.

VOLUME VI

CONSERVATION OF MATERIALS

7.1

PAINT

COMPOSITION AND PROPERTIES:

OIL-BASED PAINTS

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: R. SKANES

CONTENTS

1.0 INTRODUCTION

- 1.1 SCOPE
- 1.2 DEFINITIONS

2.0 PROPERTIES OF PAINTS

- 2.1 COMPOSITION
- 2.2 FORMULATION

3.0 OIL-BASED AND SYNTHETIC RESIN BINDERS

- 3.1 NATURAL OILS
- 3.2 ALKYD RESINS
- 3.3 URETHANES
- 3.4 EPOXIES AND SILICONES

4.0 PIGMENTS AND PIGMENT EXTENDERS

- 4.1 WHITE PIGMENTS
 - 4.1.1 *Basic Carbonate White Lead*
 - 4.1.2 *Zinc Whites*
 - 4.1.3 *Zinc Sulfide and Lithopone (Zinc sulfide plus calcium sulfate)*
 - 4.1.4 *Titanium Dioxide (TiO₂)*
- 4.2 COLOURED PIGMENTS
 - 4.2.1 *Yellow Pigments*
 - 4.2.2 *Orange Pigments*
 - 4.2.3 *Green Pigments*
 - 4.2.4 *Blue Pigments*
 - 4.2.5 *Red Pigments*
- 4.3 PIGMENT EXTENDERS

5.0 THINNERS

- 5.1 TURPENTINE
- 5.2 HYDROCARBONS

6.0 ADDITIVES

- 6.1 DRIERS
- 6.2 ANTI-FLOODING AGENTS
- 6.3 ANTI-SKINNING AGENTS
- 6.4 PIGMENT WETTING AGENTS
- 6.5 PRESERVATIVES
- 6.6 THIXOTROPIC AGENTS
- 6.7 VISCOSITY CONTROL AGENTS

7.0 SOURCES

8.0 TABLES

9.0 BIBLIOGRAPHY

1.0 INTRODUCTION

This article describes the composition and properties of oil-based paint finishes that have been or can be applied to historic structures in Canada. It will help restoration personnel in the analysis and reproduction of historical coatings. A discussion of currently available oil-based paints and potentially applicable substitutes is included.

The first well-documented types of architectural paint included both water-based paints – with binders (such as glue) or without binders (such as whitewash) – and oil-based paints using animal fat or vegetable oil binders. However, many period structures appear to have been unpainted until industrialization of the paint industry (well into the 19th-century) and the ready availability of superior oil-based paints.

Premixed oil paints were first marketed in the 19th-century. Extensive exploitation of linseed oil (obtained from the flax plant) and pigment-grade zinc oxide (as well as white lead) produced a rapid expansion of the paint manufacturing industry. Other natural oil binders were also used with, or instead of, linseed oil (for example, tung oil, also known as wood oil, or poppy seed oil).

Improved water-based paints, such as casein, gained some popularity during the early part of the 20th-century, but soon became less in demand because of the development of synthetic alkyd resins. Major changes have occurred in the manufacture of paints and the operation of the paint industry during the past fifty years. New synthetic materials and new methods of manufacture have changed painting from a rule-of-thumb art to a highly complex science.

1.1 SCOPE

This article provides a cursory description of the properties of period oil paints and 20th-century synthetic oil-based paint products. It includes a brief explanation of the composition and formation of period paint, period and current oil-based binders, pigments, thinners and additives. Some of the more common synthetic resin paint products are also briefly described.

1.2 DEFINITIONS

Paint, for the purposes of this article, is any liquid material that, when spread in a thin layer, solidifies into a film that obscures the surface on which it is applied (see Ashton).

A paint is essentially a mixture of pigments with hiding power and a binder that holds the pigments together on a surface in a thin layer. The binder is generally thinned to aid in paint application. In oil-based paint, the binder is usually dissolved in an organic solvent.

For additional information on period paints and potentially applicable substitutes, consult the sources listed in 7.0 and the bibliography in 8.0 below. (Varnishes, lacquers and drying-oil coatings without pigments are not considered paints for the purpose of this definition.)

Pigment: a powder added to a paint to impart colour and to help hide, decorate and protect the surface on which it is applied.

Additive: any solid or liquid added to a paint to impart specific physical properties.

Binders: the solid or liquid ingredient which holds together the pigments and additives of a paint. Binders can be thinned with organic solvents (for example, mineral spirits) or water. In solvent-thinned paints, the binders are normally liquids; in water-based paints, they are normally solids. The preferred 19th-century binder was linseed oil.

Thinner: also known as reducer or solvent, is any aqueous substance added to aid paint application by thinning the binder. The most important 19th-century thinners included gum spirits (turpentine) and benzene (petroleum distillate).

Paint Vehicle: the combination of binder plus thinner in a paint formulation.

Oil-based Paint: for the purposes of this article, “oil-based” includes any paint with an oxidizing binder dissolved (or soluble) in an organic solvent. These paints include natural oils and alkyls (synthetic oils).

Alkyd Paint: synthetic oil-based paint utilizing alkyd resin as the binder. Alkyd paints are sometimes imprecisely referred to as “oil paints” because they are oil-based. Both natural oil paint and alkyd (or synthetic oil) paint can be classed as an oxidizing vehicle paint or oil-based paint.

Oil Paint: for the purposes of this article, “oil paint” is defined as a natural oil-based paint (commonly, though not always, utilizing linseed oil – raw and boiled) as the binder. Oil paint is of limited availability at the present time, mostly replaced by alkyds (and more recently, latexes).

Synthetic Resin Paint: consists primarily of resins and plasticizers as well as pigment and thinner. The vehicle is a non-drying oil type of polymer such as epoxy resin, silicone alkyd or styrene polyester. Synthetic resin paints are sometimes grouped with oil-based paint products, as opposed to water-based paints.

Solvent-based Paint: oil-based paints, synthetic resin paints, lacquers and other organic solvent thinner coatings are sometimes grouped as solvent-based or solvent-thinned paint. More narrowly defined, “solvent-based paint” refers to the lacquers only, where drying occurs solely by evaporation of the organic solvent.

Water-based Paint: any non-oil-based paint with the pigments (and binder) either dispersed or dissolved in water. These include polyvinyl acetates and acrylics (latexes), also known as emulsion paints. Whitewash, distemper and calcimine were important period water-based paints.

Dispersed Binder: any solid binder that is dispersed (that is, not dissolved) in water. These paints are known as latex emulsions and include polyvinyl acetates, acrylics, styrene-butadienes and emulsified latex alkyds.

Dissolved Binder: any binder that is dissolved – that is, soluble and in solution. These paints include the older water-based coatings such as whitewash (lime-based paint), distemper paint (whitewash, plus glue or egg white), calcimine (distemper paint in which zinc white is substituted for lime) and casein paint (distemper paint with curdled or skimmed milk added) and the older solvent-thinned binders such as linseed oil. Newer dissolved binders include those with soluble alkyds and other synthetic oil-based binders.

Film Formation: the process by which paint changes from a liquid to a solid. Oil-based paints dry and harden when their binders are exposed to oxygen in the atmosphere. The binders are oxidized as the organic solvents evaporate from the dissolved binder and make room for the oxygen. The resulting coating has less volume, but more weight (through the addition of oxygen).

By contrast, most water-based paints harden when their solid (dispersed or dissolved) binders lose water by evaporation. The tiny particles are drawn together as they dry by the action of additives in the mixture (called coalescing agents) and form a continuous film. The resulting coating loses volume and weight by the evaporation of water.

2.0 PROPERTIES OF PAINTS

The physical and aesthetic properties of a paint are affected by the types of binder, pigment and thinner in the mixture, by the proportion of these ingredients and by the type and amount of special additives. For example, the proportion of binder and thinner to pigment affects gloss, flexibility, tensile strength, permeability and washability. The lower the pigment content, the higher the gloss and the harder the coating.

Additives can affect such properties as spreadability, hardness, tendency to mildew, ultraviolet degradation, drying time, discolouration and fire resistance.

2.1 COMPOSITION

Fig. 1 illustrates the basic composition of oil-based paints and their manner of film formation. As this simplified diagram shows, the exposure of the thin wet paint film to air causes the organic solvent to evaporate while the binder oxidizes (absorbs oxygen).

2.2 FORMULATION

The formulation and use of paints is highly sophisticated. The ingredients of a paint, their proportions, the preparation of the surface, the method of application and so on, all contribute to the properties of the coating. The ingredients of period and contemporary oil-based paints and of the properties they impart to the paint are discussed below.

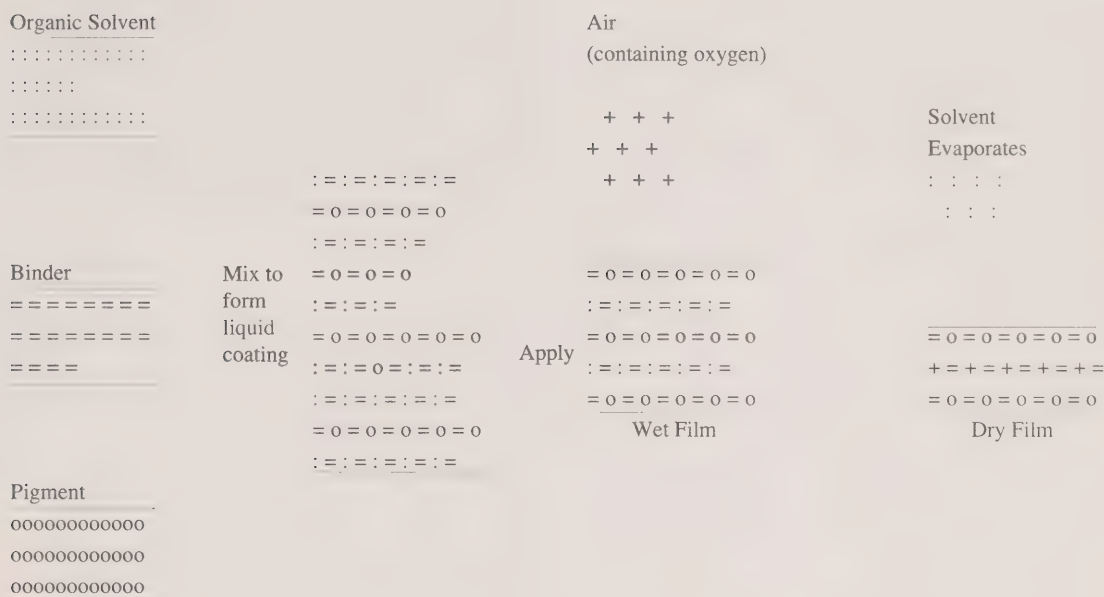


Fig. 1 Generalized Composition of Oil-based Paints and Their Manner of Film Formation

3.0 OIL-BASED AND SYNTHETIC RESIN BINDERS

3.1 NATURAL OILS

In the past, almost all oil-based paints contained natural oil binders made from vegetable oils (hence the term “oil” paint). The most effective binder was linseed oil manufactured from flax seed. Soybean, tung, fish, nut and mineral oils (that is, petroleum products) were less important and generally not used on their own, but added to the basic linseed binder to cheapen or improve the final product.

Although linseed oil can form a dry, flexible, waterproof film by reacting only with oxygen in the air, another ingredient, white lead, invariably has been added. The lead, technically classed as a pigment, reacts with the oil to form an insoluble lead soap which gives the dried paint an increased life expectancy.

The slow drying of natural oil paints, usually at least two to three days, generally was reduced to one to two days by

including drying elements in the formulation to enhance oxidation and by using a combination of natural and boiled linseed oils. Boiling the oil drives off most of its moisture, allowing it to dry quickly to a hard film. These paint adulterants, however, also shortened its life expectancy. A typical oil paint in a moderately exposed application could be expected to last for approximately two to three years. The synthetic oil paints of today have four times this life expectancy.

Natural oil paints perish by chalking – the gradual powdering away of the surface. To correct this, various ingredients were added. Sublimed white lead, which is chemically inert and does not unite with linseed oil, was often included, as was zinc white, which dries to a hard, brittle film. These anti-chalking ingredients were never completely successful and the tendency to chalk still characterizes natural oil paints. Chalking, however, does have one advantage: generally no scraping or burning is required before repainting.

The colour stability of linseed oil paint is affected not only by the type of pigment used in the formulation, but also by the tendency of the linseed-white lead combination to yellow during oxidation. This is particularly noticeable in white paints

where coloured pigments do not disguise the yellowing. The usual solution was to replace part of the white lead with zinc white, an inert white pigment which does not react chemically with linseed oil during oxidation and to add various blue pigments to the formulation that accentuate the white colour and disguise the yellow. The results were only moderately successful.

Raw linseed oil binder comprises 50 to 70 percent by volume of a typical oil paint. Other ingredients and their relative proportions are shown in Fig. 2.

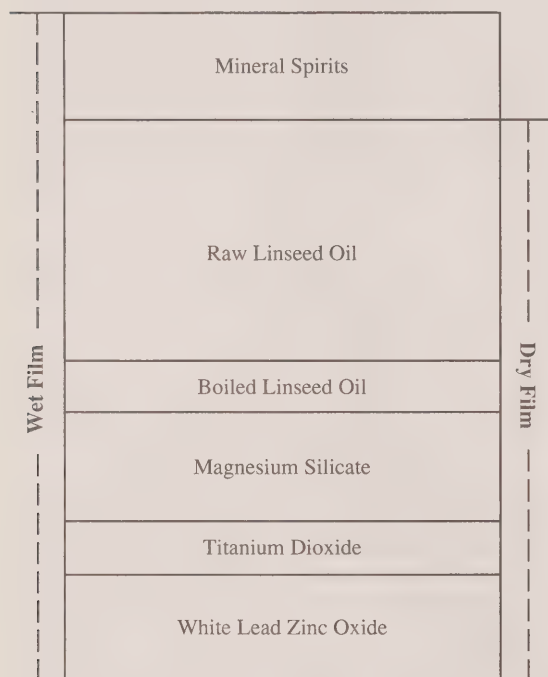


Fig. 2 Composition of a Typical Oil Paint by Volume

Linseed oil, for a long time, was the most common oil-based binder. During the 1930s, however, a synthetic oil material known as alkyd resin was substituted for linseed oil. The resin was not only less expensive to manufacture, but also produced a more durable paint. These two advantages, coupled with legislation regulating the sale of paints containing lead (an ingredient vital to the quality of linseed oil paints), has resulted in the total domination of alkyd resins in the oil-based paint industry. Linseed oil (or natural oil) paints are still available from some manufacturers, but at a substantially

higher cost than alkyds. Much of the oil paint used for the Canadian Parks Service's historic structures is not purchased commercially, but prepared on site using period methods.

Recent developments in the paint industry include water-soluble linseed oil binders. Unlike period linseed oil, the new product is dispersed (that is, not dissolved) in the thinner. These new products are water-based and not considered to be "oil paint."

3.2 ALKYD RESINS

Essentially, alkyd resins are treated vegetable oils which have had some of their deleterious properties removed in a high-heat reaction between the fatty acids in the oil and a fatty alcohol such as glycerine or pentaerythritol. The resulting product is termed a polyester.

Paints based on alkyds have many advantages over natural oil-based paints. They are less expensive and have good durability, flexibility and gloss retention. They have acceptable solvent resistance, toughness, heat resistance and colour retention. Like natural oil-based paints, they dry by oxidation and harden fairly rapidly. They are used in flat or glossy architectural coatings and in factory-applied, air-dried or oven-baked finishes. They are compatible with other resins and oils and impart desirable alkyd characteristics to them.

Alkyds are ideal binders, because they can wet and disperse pigments readily and handle a wide range of volume concentrations. As a result, they are used in coatings that must penetrate a surface without leaving soft pigment residues behind (as is often the case in natural oil-based paints); or they are used in flat house paints that do not penetrate much, but flow and level well. They make quality high-gloss enamels that are high in resin and relatively low in pigment.

The resin content of alkyd paints is generally between 50 and 70 percent of the paint volume. The more resin, the more flexible and also the softer, the less viscous and the more easily damaged by solvents is the film. The colour retention of alkyd resins is usually better than that of the vegetable oils from which they were made. However, when yellowing oils such as linseed are the chemical base, oxidation may produce some discolouration. When soybean or safflower oil is the base, colour integrity is generally better.

Alkyds are frequently used on historic structures as a substitute for oil paints. In some cases (for example, the RCMP St. Roch, restored to its 1944 appearance), the period paints may have

utilized alkyd resin binders. The superior durability and reduced level of toxicity of alkyd paints are desirable characteristics.

Alkyd-based paints should not be used over freshly constructed alkaline surfaces such as concrete, masonry or plaster, without first applying a prime coat or allowing the surface to cure for the recommended time. Alkyds have only fair durability in mildly corrosive environments.

3.3 URETHANES

Urethane binders are a more recent form of alkyd resin. They are made by modifying a key ingredient in alkyd manufacture. Often they are termed urethane alkyds or "uralkyds." Urethanes perform like alkyds, but are better in a number of ways. They produce a harder, more flexible film; they have better abrasion, solvent and chemical resistance. Unlike alkyds, however, they tend to yellow rapidly in sunlight and to lose their gloss on exterior exposures.

Of the many types of urethanes sold, the most common are moisture-, heat-, and two-part catalyst-cured. Their main architectural use is on floors and walls where durability and chemical resistance are important. (The characteristics of urethane paints are listed and compared to other common paints in Table 1.)

3.4 EPOXIES AND SILICONES

Epoxy resin binders have been sold in North America since 1950. They have very limited use without the resins, additives and catalysts included to produce a tough, long-lasting, albeit expensive, coating.

Epoxies are used on walls and floors where heavy use is expected or maximum cleanliness is desired. When applied on exteriors, an epoxy will chalk. This chalking is not excessive, however, and takes six to twelve months to show. Epoxies, therefore, share with linseed oil paints the advantage of having the surface easily and continuously washed clean by rainfall as a result of this chalking characteristic.

The acid resistance, brilliant gloss, washability and hardness of epoxy paints are due to additives such as esters, polyester and coal tar.

Silicones, perhaps the most expensive of all the synthetic resin binders, have an important characteristic that justifies

their cost – weatherability. Because of the resin's resistance to oxygen, the coating maintains its colour and gloss even when exposed to temperatures in the 275°C to 335°C range.

Silicone resins are generally combined with other resins such as alkyds, epoxies and acrylics to make air-dried paints for fluid application on architectural surfaces and baking enamels for factory application of coatings on architectural metalwork. In the latter case, the coating is often guaranteed against fading and film failure for up to 20 years.

Most silicone-based products are proprietary and, hence, are not as widely sold as the more common coatings. They merit consideration, however, where long-term survival of the finish is important, particularly in a corrosive atmosphere and where cost is a secondary consideration.

Because of their highly specialized nature and application, a complete description of these and other new products is beyond the scope and intent of this article. Contact manufacturers directly for more detailed information on properties, specifications and uses.

4.0 PIGMENTS AND PIGMENT EXTENDERS

The function of a pigment is to impart colour and to hide the underlying surface or to combine with some other substance to give the paint certain properties (for example, corrosion inhibition, ultraviolet absorption, durability, toughness or flexibility).

All white pigments hide and decorate to some extent, but others such as white lead, zinc oxide and antimony oxide, are also reactive and become components of chemicals serving a particular purpose in a coating. Most coloured pigments require some white hiding pigment (in the past white lead; today, almost always titanium dioxide).

Cost and availability are as important as hiding and reactive capabilities in selecting a pigment. In formulations which include costly pigments, cheaper (but less desirable) pigment "extenders" are used. Extenders are important not only for their economy, but also for the body and bulk they give to a coating. Virtually all paints sold today, regardless of cost, include at least a small percentage of extenders. The best hiding pigments are used only to the extent necessary to provide opacity; the rest of the pigmentary duty is carried out by extenders.

4.1 WHITE PIGMENTS

4.1.1 Basic Carbonate White Lead

White lead (produced by exposing metallic lead to vinegar and CO_2) was historically the most important pigment in oil-based paints and usually constituted about 35 percent of the paint mixture. It is a reactive pigment combining with linseed oil binder to increase durability and life expectancy, elasticity and adhesion. In conjunction with coloured pigments, it usually provides increased opacity. Its main disadvantage is a tendency to chalk. Life expectancy in an exposed location is generally two to three years.

Note: Other leads used in period paints with similar, but inferior properties to carbonic white lead, were sulfate white lead (known also as sublimed lead) and silicate white lead (a composite of lead sulfate plus silica). Today, the use of lead in paints is regulated by legislation.

4.1.2 Zinc Whites

Zinc oxide is another pigment that was used extensively in oil-based paints. It is a reactive pigment which combines with acid components in paint to form zinc soap, a compound that improves film hardness, retards chalking, adds brilliance to white colours, helps retain colour integrity (by absorbing ultraviolet rays), controls mildew and imparts body to the paint. Zinc oxide was second only in importance to white lead in period paint formulations.

4.1.3 Zinc Sulfide and Lithopone (Zinc sulfide plus calcium sulfate)

These two pigments were used together in most coloured period paints. They are non-reactive pigments used to prevent separation of the coloured pigments in the can and on the surface. Zinc sulfide is slightly yellowish and, consequently, seldom used in modern white paints, although occasionally included in tinted mixtures. These pigments tend to chalk, causing eventual failure of the paint film.

4.1.4 Titanium Dioxide (TiO_2)

Because of its superior hiding capabilities, this pigment became popular during the 1930s. It is a non-reactive pigment used only for its white opacity; it imparts no protective properties to a paint film. Although expensive to manufacture,

TiO_2 has such good hiding power that, relative to other pigments, very little of it has to be used. For this reason, it provides the same hiding coverage at one-fifth the cost of zinc oxide and one-seventh the cost of white lead.

Because TiO_2 has no protective qualities, other more expensive reactive pigments must be used in the formulation to make up this deficiency. Often, for economy, these more expensive substances are left out. The resulting paint is inferior in both quality and life expectancy.

4.2 COLOURED PIGMENTS

Coloured pigments can be divided into those that are inorganic and those that are organic. The general advantages and disadvantages of each are summarized in Table 2.

Because there are hundreds of coloured pigments in these two categories, only those pigments which have noteworthy period or contemporary application are discussed. Pigments are presented in the appropriate colour division and their performance characteristics are emphasized.

4.2.1 Yellow Pigments

- a. Iron Oxide:
inorganic pigment; basic ingredient of period ochre colours; substantial contemporary use.
Advantages: lightfast; non-bleeding; non-toxic; high hiding; good chemical resistance; non-reactive; available in low-hiding grades for transparent and translucent films.
Disadvantages: poor gloss retention; "dirty" colours.
- b. Nickel Titanate Yellow:
inorganic pigment; substantial contemporary use.
Advantages: lightfast; exterior durability; chemical resistance, withstands high temperatures.
Disadvantages: tendency to chalk; weak in tinting strength.
- c. Hansa Yellow (Toluidine Yellow):
organic pigment; substantial contemporary use.
Advantages: available from primrose to medium yellow; lightfast; alkali and acid resistant; lead-free.
Disadvantages: poor hiding; bleeds badly; poor heat resistance; high cost; poor lightfastness in tints.
- d. Chrome Yellow Lead Chromate:
inorganic pigment; used extensively in period paints; due to lead content, use in contemporary paint is regulated by legislation.
Advantages: clean, crisp colour; low cost; high hiding;

non-bleeding; good durability, declining with lightness.
Disadvantages: poor alkali and soap resistance; tendency to darken on exposure; contains lead; discolours in presence of sulfides.

e.. Zinc Yellow (zinc potassium chromate):

inorganic pigment; used extensively in period and contemporary paints.

Advantages: prevents deterioration of aluminum and magnesium; yields low-priced, clean, green shades with phthalocyanine blue; rust-inhibitive; lightfast.

Disadvantages: greenish-yellow; highly reactive in some resins, must be compounded carefully; mainly suitable for primers where topcoat is applied early because of its slight water solubility; poor hiding.

f. Benzidine Yellow:

organic pigment; contemporary use.

Advantages: twice the tinting strength of Hansa yellow; lead-free; lightfastness; good chemical and bleed resistance.
Disadvantages: high cost; low hiding power; high oil absorption.

g. Cadmium Yellow:

inorganic pigment; extensive period and contemporary use.
Advantages: most permanent yellow known; unaffected by sulphur gases, light and air.
Disadvantages: high cost; difficult to manufacture; cannot be mixed with lead-based pigments.

4.2.2 Orange Pigments

a. Chrome Orange:

inorganic pigment; extensive period use; limited contemporary use due to lead content.

Advantages: low cost; non-bleeding; lightfast; rust-inhibitive.

Disadvantages: contains lead; susceptible to darkening; poor hiding and soap resistance compared with molybdate chrome orange.

b. Molybdate Chrome Orange:

inorganic pigment; limited period use; substantial contemporary use.

Advantages: low cost; non-bleeding; combines with organic reds to give low-cost, high-intensity, durable finishes of various shades of red.

Disadvantages: contains lead; poor alkali and soap resistance; tends to darken on exposure.

c. Benzidine Orange:

organic pigment; limited period use; substantial contemporary use.

Advantages: high colour intensity; high tinting strength; nontoxic; good chemical resistance.

Disadvantages: high cost; poor lightfastness; poor bleed resistance; low hiding power.

4.2.3 Green Pigments

a. Chrome Green:

inorganic pigment; extensive period use; contemporary use limited because of lead content.

Advantages: low cost; wide variety of shades because inorganic iron blue and chrome yellow ingredients can be varied; good hiding; non-bleeding.

Disadvantages: poor alkali resistance; contains lead; moderately lightfast; tends to flood and float.

b. Chrome Oxide:

inorganic pigment; extensive period and contemporary use.
Advantages: nonreactive; good heat, light and chemical stability; high hiding.

Disadvantages: olive green shade; poor gloss retention on exterior exposure; low tint strength (about one-fourth that of chrome green).

c. Hydrated Chrome Oxide:

inorganic pigment; substantial period and contemporary use.
Advantages: cleaner, brighter green than chrome oxide; excellent exterior durability.

Disadvantages: low tinting strength; poor blister resistance.

d. Phthalocyanine Green:

organic pigment; substantial contemporary use.

Advantages: clean colour; high transparency in metallics; lightfast; resistant to chemicals and bleeding; good tinting strength.

Disadvantages: high cost; tendency to bronze on exposure.

4.2.4 Blue Pigments

a. Ultramarine Blue:

inorganic pigment; very important in period and contemporary paints.

Advantages: reddish tone; brilliant; low cost; alkali resistant; good infra-red reflectancy.

Disadvantages: low hiding; very poor acid resistance; poor tinting strength; poor outdoor durability.

b. Iron Blue (Prussian Blue):

inorganic pigment; second only in importance to ultramarine in period and contemporary paints.

Advantages: low cost; high tint strength; good durability in dark tints; nonbronzing.

Disadvantages: poor lightfastness in light tints; poor can storage stability and alkali resistance which can be overcome somewhat by blending phthalocyanine blue.

c. Phthalocyanine Blue:

organic pigment; used in contemporary paints.

Advantages: lightfast; heat-stable; chemical resistant; high in tint strength and lightfast; bleed resistant.

Disadvantages: high cost; tends to bronze in dark shades, which can be overcome by blending with iron blue.

4.2.5 Red Pigments

a. Red Iron Oxide:

inorganic pigment; used extensively in period and contemporary paints; forms the basis of period red ochre and sienna.

Advantages: low cost; high hiding; lightfast; good chemical resistance.

Disadvantages: "dirty" colour; poor gloss retention; low tint strength.

b. Red Lead:

inorganic pigment; very important historically; limited use today because of lead content.

Advantages: excellent film integrity for exterior paints; high rating for rust inhibition in primers.

Disadvantages: low in hiding; usable only for primers, since it fades; is actually orange rather than red.

c. Para Red:

organic pigment; extensive period and contemporary use.

Advantages: low cost; good hiding; good acid and alkali resistance; lightfast in deep tones.

Disadvantages: bleeds badly when used for tinting; poor lightfastness in tints.

d. Toluidine Red:

organic pigment; substantial contemporary use.

Advantages: bright; relatively cheap; exterior durability; lightfast in deep tones; excellent acid and alkali resistance.

Disadvantages: poor bleed resistance.

4.3 PIGMENT EXTENDERS

The function of a pigment in a paint is not only to hide and decorate the underlying surface, but also to provide body and bulk to the coating so that it spreads evenly, does not sag or penetrate too deeply and dries to the appropriate gloss. Most pigments with good hiding capabilities are expensive. To use more than is necessary for coating opacity would be wasteful and uneconomical. Consequently, pigment extenders, low cost

materials that have all the necessary properties of pigments but poor hiding power, are used to give body and bulk. Thus, for example, titanium dioxide, which is the best but most expensive white hiding pigment, is used only to the extent required for opacity (see also 6.0 below).

Since the integrity of a coating often depends on the judicious use of extender pigments, the following descriptions of these materials emphasize the properties they impart to the paint.

a. Calcium Carbonate (also known as whiting, calcite, ground limestone or chalk):

extensive period and contemporary use; imparts tint retention, mildew resistance and brightness; controls spreadability and penetrability; often used historically in linseed oil paints.

b. Clay (Aluminum Silicate):

extensive period and contemporary use; employed as a thickener and sag control agent; improves stain resistance and washability.

c. Talc (Magnesium Silicate):

extensive period and contemporary use; retards cracking; helps flatten gloss.

d. Silica (fine quartz diatomaceous earth):

extensive period and contemporary use; offers high bulking properties, reduction of gloss and high rate of oil and binder absorption.

e. Sulfate (Barium, Calcium):

barium sulfate and calcium sulfate (or gypsum) are used in formulating sanding primers because they have low binder demand and are soft; limited period and contemporary use.

5.0 THINNERS

Most binders used in paints are so viscous that they would be unable to adhere to the surface even if they could be spread. To make them spreadable and manageable, they must be dissolved. Hence the addition of solvents or thinners to paint formulations.

These thinners, however, do more than merely thin coatings. They also wet the surface on which the paint is applied and contribute to adhesion by penetrating the pores and crevices, taking the paint with them. During storage in the can, they provide a "head" of vapour that helps retard the skinning caused by oxidation. They also play a role in laying down

uniformly thick films, that is, levelling. The most common thinners are described below.

5.1 TURPENTINE

Historically, turpentines were the most important thinners for oil-based paints. Turpentines are derived from wood or wood sap (generally from pines). Turpentine's toxicity, high cost and strong odour account for its general decline. Today, most turpentines have been replaced by mineral spirits.

- a. Gum spirits:
generally referred to as the product from Southern pine sap. Favoured period thinner because of its sweet smell (less strong than the other turpentine products) and minimum discolouring of white paints.
- b. Wood spirits (also known as wood turpentine or oil of turpentine):
tarry smelling turpentine produced from distillation of the wood of pine trees. Wood spirits were reported to evaporate less quickly than gum spirits.

5.2 HYDROCARBONS

Hydrocarbons are used today more than all other types combined. They have extensive period use and are mainly derived from petroleum and the distillation of coal tar. Basically two types of hydrocarbons are used: aromatics and aliphatics, that have less solvent power than aromatics.

- a. Mineral spirits:
the most common solvent for ordinary architectural paints; available in either standard grade or odourless. (The former has two-thirds higher solvency capabilities than the latter, but has a somewhat pungent odour.) Mineral spirits are a relatively new product and are generally used in place of turpentine.
- b. Painter's naphtha:
preceded mineral spirits as the favoured hydrocarbon thinner; its low flame-point and high speed evaporation eventually made it unpopular; used today mainly in spray paints where rapid evaporation is important.

6.0 ADDITIVES

The most common period and contemporary additives used to impart specific coating properties to a paint are described below (see also 4.2 above).

6.1 DRIERS

Driers are catalysts (or oxidizing agents) which speed up the reaction of oxygen in the atmosphere with such binders as alkyds or vegetable oils so that the paint will dry in a reasonable time. A typical alkyd may take a week to dry without the catalyst; linseed oil may take many weeks. In the past, salts of lead or manganese and Japan driers, were used extensively. Today, cobalt and manganese salts are favoured, lead having fallen from use because of its toxicity.

6.2 ANTI-FLOODING AGENTS

Anti-flooding agents, or deflocculators, are included in many colour formulations to keep the white hiding pigments from separating from the colour particles. Silicone oils and fatty acid esters are used for this purpose in solvent-reduced coatings. Without them, colours may separate either in the can or after application during drying. There is no equivalent anti-flooding agent for period linseed oil paints.

6.3 ANTI-SKINNING AGENTS

Anti-skinning agents are needed for paints that dry by oxidation, particularly quick-drying materials like floor or four-hour enamels. These agents have to retard oxidation in the can but must disappear when the coating is applied. The most popular anti-skinning agents are butyraldoxime and methyl ethyl ketoxime because they are so volatile in open air that they do not hinder drying and because they have no effect on colour.

6.4 PIGMENT WETTING AGENTS

Pigment wetting agents help binders coat each particle of pigment, which means they must help replace air around the pigment. Estimates put the amount of space consumed by air in a bag of pigment at 80 percent. Not all pigment is surrounded by air; some is lumped together in agglomerates which must be broken up by milling. Pigment wetting agents speed the separation of particles and help to keep them

separated. Without them, dispersion would be inadequate, with consequent inconsistencies in hiding, gloss, colour and texture. For solvent-thinned paints, lecithin and esters of fatty acids are used.

6.5 PRESERVATIVES

Preservatives eliminate bacterial contamination, which leads to enzyme degradation of cellulosic thickeners and other organic matter in paint. Phenyl mercury salts have been used for many years, but lately various substitutes have been introduced.

6.6 THIXOTROPIC AGENTS

Thixotropic agents provide body to a paint so that it appears to have a creamy, easily spread consistency. When pressure is applied, either by dipping the brush in the can or brushing on a surface, the paint thins; the creamy consistency returns when pressure ceases. This thick-thin ability is imparted by thixotropic agents. A paint containing proper thixotropic agents requires little stirring after storage, because its body holds the pigments and other materials in place. The result is a material that is easy to spread and will not sag on the surface since it regains its body after spreading. These materials also function as viscosity control agents.

6.7 VISCOSITY CONTROL AGENTS

Viscosity control agents permit a paint to hold a definite range of thickness during storage in the can. They are indistinguishable from the thixotropic agents and are listed separately only for classification purposes. Solvent-thinned paints are controlled by amine-treated clays, usually a type called bentonite or by waxy materials derived from hydrogenated castor oil. Some viscosity control of solvent-thinned paints is obtained from certain colloidal silicas or aluminum stearate.

7.0 SOURCES

The following is a partial list of available sources for engineering and architecture staff to obtain additional information about the composition and properties of oil-based paints (see also 8.0 below).

Conservation Research Division
Canadian Conservation Institute
National Museums of Canada,
1030 Innes Road,
Ottawa
K1A 0M8

Conservation Research Objects Section
Conservation Division
National Historic Sites Branch
Canadian Parks Service,
1570 Liverpool Court
Ottawa
K1A 0H3

Period Engineering Section
Heritage Conservation Program
Architecture and Engineering Services
Jules Leger Building, 25 Eddy St.
Hull, PQ
K1A 0H3

8.0 TABLES

TABLE 1 – PROPERTIES AND CHARACTERISTICS OF COMMON SOLVENT-THINNED BINDERS

PROPERTIES AND CHARACTERISTICS	BINDER			
	Oil (linseed)	Alkyd	Urethane (moisture-cured)	Epoxy
Adhesion	VG	VG	G	E
Hardness	F	G	E	E
Flexibility	G	G	VG	E
Resistance to				
Abrasion	F	G	E	E
Acid	P	F	E	G
Alkali	P	F	VG	E
Detergent	F	F	VG	E
Heat	F	G	G	G
Solvents	P	F	E	E
Water	G	G	VG	G
Brushability	G	G	F	F
Odour	strong	strong	strong	strong
Method of Cure	oxygen	oxygen	moisture	chemical
Gloss Retention	F	F	F	P
Colour:				
Initial	G	E	E	G
Yellowing				
(clear)	P	slight	moderate	n/a
Fade Resistance	G	E	F	F
Chalk Resistance	F	G	F	F
Use on				
Wood	E	E	E	E
Fresh, dry				
concrete	NR	NR	G	E
Metal	G	VG	G	E
Interior	VG	E	G	E
Exterior:				
Rural	G	E	G	E
Seashore	F	G	VG	E
Industrial Areas	P	P	F	E
Excellent	E	Poor	P	
Very Good	VG	Very poor	VP	
Good	G	Not recommended	NR	
Fair	F	Not applicable	N/A	

Source: (Based on a composite of published tables. See bibliography 9.0.)

Reprinted by permission of the National Research Council of Canada.

TABLE 2 – ADVANTAGES AND DISADVANTAGES
OF ORGANIC AND INORGANIC PIGMENTS

ADVANTAGES	DISADVANTAGES
Inorganic:	
<ul style="list-style-type: none">• Non-bleeding in organic solvents• Superior heat resistance• Less costly per gram• Opaque	<ul style="list-style-type: none">• Low tinting strength
Organic:	
<ul style="list-style-type: none">• Some are slightly soluble in organic solvents• Strong (tends to offset high cost)• Transparent• More intensive	<ul style="list-style-type: none">• Less heat resistance• More costly per gram

9.0 BIBLIOGRAPHY

Ashton, H.E. n.d. *Paint – What is it?* Canadian Building Digest, No. 76. National Research Council, Ottawa.

_____. n.d. *Paints and Other Coatings*. Canadian Building Digest, No. 78. National Research Council, Ottawa.

Banov, A. 1973. *Paints and Coatings Handbook for Contractor. Architects, Builders, and Engineers*. Structures Publishing Company, MI.

Canadian General Standards Board. 1970. *Primer, Alkyd, for Hardwood*. (1-GP-1M). Ottawa.

_____. 1973. *Primer, Wood, Exterior*. (1-GP-55E).

_____. 1977. *Enamel, Interior, Low Gloss, Alkyd*. (1-GP-202M).

_____. 1977. *Enamel Interior Undercoater*. (1-GP-38M).

_____. 1977. *Low Flash Petroleum Spirits Thinner*. (1-GP-5M).

_____. 1977. *Petroleum Spirits Thinner*. (1-GP-4M).

_____. 1977. *Thinner, High Solvency*. (1-GP-70M).

_____. 1978. *Enamel, Exterior, Gloss Alkyd Type*. (1-GP-59M).

_____. 1978. *Enamel, Interior, Gloss, Alkyd Type*. (1-GP-60M).

_____. 1978. *Enamel, Interior, Semigloss, Alkyd Type*. (1-GP-57M).

_____. 1978. *Finish, Interior, Alkyd, Flat*. (1-GP-118M).

_____. 1978. *Primer, Alkyd, Wood Exterior*. (1-GP-189M).

_____. 1978. *Primer, Marine, for Steel*. (1-GP-48M).

_____. 1978. *Primer, Red Lead, Iron Oxide, Oil Alkyd Type*. (1-GP-140M).

_____. 1978. *Primer-Sealer, Wall, Interior, Solvent Type Q*. (1-GP-68M).

_____. 1978. *Standard Paint Colours*. (1-GP-12C).

_____. 1979. *Enamel, Exterior and Interior, for Floors*. (1-GP-73M).

_____. 1979. *Enamel, Heat Resistant, Interior and Exterior*. (1-GP-76M).

_____. 1979. *Enamel, Interior for Concrete Floors*. (1-GP-66M).

_____. 1979. *Paint, Lighthouse, White*. (1-GP-109M).

_____. 1979. *Primer, Basic Lead Silico-Chromate: Oil Alkyd Type*. (1-GP-166M).

_____. 1979. *Primer, Structural Steel: Alkyd Type*. (1-GP-40M).

_____. 1980. *Boiled Linseed Oil*. (1-GP-2M).

_____. 1980. *Enamel, Alkyd, Marine, Exterior*. (1-GP-61M).

_____. 1980. *Enamel, Alkyd, Marine, Interior: Fire Retardant*. (1-GP-52M).

_____. 1980. *Enamel, Exterior, Basic Lead Silico-Chromate: Alkyd Type*. (1-GP-167M).

_____. 1980. *Raw Linseed Oil*. (1-GP-1M).

_____. 1981. *Exterior Alkyd House Paint*. (1-GP-28M).

_____. 1981. *Guide to the Selection of Paint Standards on Use Basis*. (1-GP-72).

_____. 1981. *Methods of Testing Paints and Pigments, 5th edition*. (1-GP-71).

_____. 1981. *Paint, Traffic, Alkyd*. (1-GP-74M).

_____. 1981. *Red Lead in Oil Primer*. (1-GP-14M).

_____. 1981. *Sealer, Clear, Alkyd Type*. (1-GP-102M).

Candee, R.M. 1968. *House Paints in Colonial America*. Chromatic Publishing Co., New York.
Special edition from *Color Engineering* magazine excerpts.

Cawley, F.D. 1978. *Property Owner's Guide to Paint Restoration and Preservation*. Technical Series No. 1. Preservation League of New York State, Albany, NY.

Consumer Reports. 1976. "Exterior Oil Paints." Vol. 41 (September), pp. 504-09.

Crown, D.A. 1968. *The Forensic Examination of Paints and Pigments*. Charles C. Thomas, Springfield, IL.

Dornsife, S.J. 1976. *Exterior Decoration: A Treatise on the Artistic Use of Colours in the Ornamentation of Buildings, and a Series of Designs, Illustrating the Effects of Different Combinations of Colours in Connection with Various Styles of Architecture*. Reprint of 1885 edition. The Atheneum of Philadelphia, Philadelphia.

Hasluck, P.N., ed. 1905. *Painters' Oils, Colours, and Varnishes*. Cassell and Company, Limited, London.

Labine, C. 1976. "Selecting the Best Exterior Paint," *The Old-House Journal*, Vol 4, No. 7 (July), pp. 1, 10-11.

Miller, K.H. n.d. "Paint Colour Research and Restoration of Historic Paint," *Bulletin of the Association for Preservation Technology*, Ottawa.

Painter's Magazine. 1909. *One Thousand More Paint Questions Answered*. New York.

Patton, T.C., ed. 1973. *Pigment Handbook, Volume II, Applications and Markets*. John Wiley & Sons, New York.

Perrault, C.L. 1976. *What Shall We Do With Our Walls? A Bibliography of Literature on Architectural Painting for Historic Structures*. Technical Preservation Services Division. National Parks Service. U.S. Dept. of the Interior, Washington, DC.

VOLUME VI

CONSERVATION OF MATERIALS

7.2

PAINT

DETERIORATION

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: ANNA KOZLOWSKI

CONTENTS

1.0 INTRODUCTION

2.0 CAUSES OF CHANGE

3.0 DETERIORATION OF PAINT FILM

3.1 MILDEW (FUNGI, MOULDS)

3.2 CHALKING

3.3 DISCOLOURATION

3.4 BLEEDING

3.5 CHECKING

3.6 CRACKING

3.7 BLISTERING

4.0 DETERIORATION OF WALL PAINTING

5.0 DETERIORATION OF VARNISHES

6.0 BIBLIOGRAPHY

1.0 INTRODUCTION

Recognizing the existing and potential defects related to paint and related finishes is helpful in establishing appropriate treatment and maintenance procedures for historic structures.

Since modern ingredients and methods of preparing paint differ from traditional practices, there is potential for incompatibility is greater in restoration work and when dealing with very old paint finishes generally. Existing and potential defects need to be recognized and understood before cleaning, removing or repainting period finishes.

The following article deals with the causes of deterioration.



Paint Deterioration

2.0 CAUSES OF CHANGE

Changes in the appearance of surface finishes may simply be the physical manifestation of a normal aging process, combined with the accretions of years of service.

They may be the result of inherent defects which can be traced to the use of improper materials, faulty surface preparation, poor workmanship or adverse environmental conditions at the time of application.

External factors such as moisture, biological activity, environmental pollution, etc., may degrade the finish or undermine the substrate to which it was applied.

3.0 DETERIORATION OF PAINT FILM

3.1 MILDEW (FUNGI, MOULDS)

Fungi and moulds feed on nutrients contained in the paint film or on dirt adhering to the surface. The growth may consist of fine filaments or coloured sporophores with spongy texture, or a combination of both. Frequently, mildew is indistinguishable from dirt.

Conditions favourable to growth of mildew are high humidity, warm temperature, darkness and lack of ventilation. Susceptible materials include damp wood, plaster and distemper paints with organic constituents such as size or casein.

A superficial infestation can be washed off; however, holes or stains may be left on the paint film after the mildew is gone. Before repainting, the surface should be sterilized or the growth may redevelop beneath the new coating.

3.2 CHALKING

Chalking results in a dull appearance accompanied by a powdery of the paint surface (the powder rubs off on the hand). Pigment is released by the photochemical breakdown of the surface layer of binder upon exposure to the weather. This process is generally associated with white or lightly tinted paints.

Rainwater carries away dirt and discolouration, regularly "freshening" the surface. Some paints, particularly greys, chalk unevenly leaving a blotchy appearance.

Excessive chalking may result if:

- the ratio of pigment to binder is too high
- the film was too thinly applied
- an inadequately prepared, porous surface absorbs too much of the binding medium

Casein paints may dust off if applied to old, dry plaster; they become insoluble only if the casein reacts chemically with the calcium oxide in fresh plaster.

3.3 DISCOLOURATION

Colour changes may occur uniformly as a result of external influences or in localized areas because of contamination from the substrate.

a. Fading:

Fading is the gradual decrease of colour intensity resulting from exposure to sunlight or to the elements. It can occur more rapidly in rural or marine environments, where ultraviolet radiation is less likely to be absorbed by atmospheric contaminants. It appears to be accelerated by the presence of moisture. Not all pigments or dyes are equally lightfast in every type of medium. The lightfastness of certain organic pigments can be reduced when they are mixed with white pigments.

Acid contaminants in the air can fade acid-sensitive pigments, such as pale shades of ultramarine blue. Yellow finishes based on lead chromes will pale from contact with sulphur dioxide in moist air. Some pigments discolour in contact with alkalis (e.g. mortar, lime plaster).

b. Yellowing:

Yellowing of white and pale shades takes place under the influence of light, heat or atmospheric pollutants such as ammonia or tobacco smoke.

c. Blackening:

Blackening or greying of paint films containing white lead was a common occurrence in industrial areas where the atmosphere was polluted with hydrogen sulfide.

3.4 BLEEDING

Bleeding into new paintwork occurred with certain organic pigments and dyestuffs if the surfaces were not properly sealed with shellac. A particularly troublesome colour known as "bleeding red" was notorious for seeping through half a dozen coats of paint.

3.5 CHECKING

Checking refers to the condition of a painted surface which is covered with a network of fine hairline cracks which do not penetrate down through all the layers to the substrate. It can result when a coating becomes too dry and brittle to move with the substrate in response to changes in temperature and humidity. It is often associated with the presence of an excessive number of layers. It can also occur if the finishing coat is applied to a softer undercoat.

The application of varnish over oil-rich undercoats will cause checking. This condition has been observed on graining work.

Paints containing yellow ochre and lamp black, which are soft and slow drying materials, are prone to cause checking when used as undercoats.

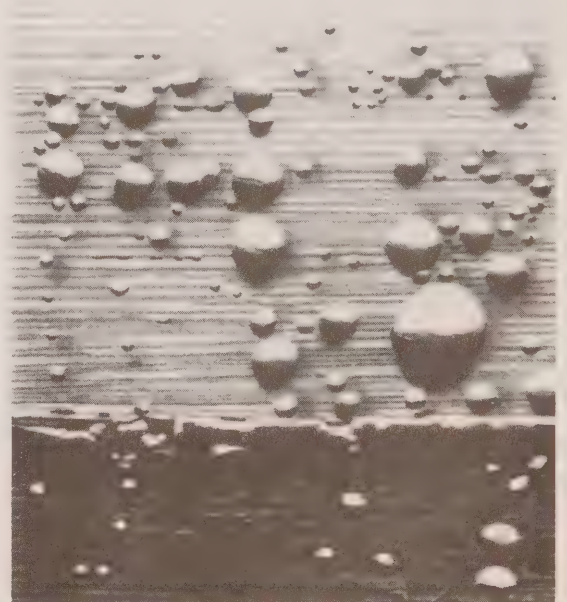
3.6 CRACKING

This is the advanced stage of checking. It can occur when a dimensionally unstable substrate is subjected to cycles of wetting and drying; coating systems which have lost some of their elasticity, will then crack under the strain. The cracks extend down to the substrate and eventually will result in flaking.

The causes are heavy film build-up, improper formulation of the coatings, application to unseasoned wood or application to improperly prepared substrates. Cracks on wood which was too dry when coated are smooth and flat. The edges of cracks can usually be felt to protrude from unseasoned wood.

Coatings applied to substrates containing depressions, cracks or any surface irregularities with sharp edges, will crack along these edges when stressed by normal aging processes.

Failure can be the result of excessive application of fillers and primers. Films containing heavy brush marks may be subject to "line" cracking.



Blistering of Paint

3.7 BLISTERING

Blisters are caused by moisture gathering beneath a dried film or by the vapourization of trapped solvents. Moisture in or behind the substrate is drawn outwards by the action of ambient heat; wherever the adhesion of the film is weak, moisture will collect to form blisters.

If solvent-rich paint is applied in direct sunlight, the top layer will dry quickly and solvents may be trapped beneath to form blisters. The problem occurs more often with paints of a dark colour.

4.0 DETERIORATION OF WALL PAINTING

Plaster substrates often contain straw, animal or vegetable fibres which are hygroscopic materials. When exposed to moisture, they can draw it into the plaster, providing favourable conditions for biological attack and deterioration resulting from frost action.

Moisture rising from the ground and evaporating from the wall may decompose the surface by the mechanism of salt crystallization. Water infiltration can cause staining, erode distemper paints and cause saponification of oil paints by the activity of alkalis present in lime plaster. Ambient moisture can deposit superficial incrustations of dirt by means of condensation.

Organic binding materials, such as gums and size, are very sensitive to fluctuations in humidity; they contract and may flake upon drying. Artificial heating can affect the stability of both painting and plaster substrate.

Sunlight bleaches organic pigment and accelerates oxidation of the binding medium.

Soot, dust and insect deposits are frequently alkaline or acidic in nature and promote deterioration.

A dirty or inadequately prepared surface is an inherent defect that causes surface paint loss. A crazed surface in an oil medium may be the result of application to an absorbent substrate.

5.0 DETERIORATION OF VARNISHES

The development of a whitish deposit accompanied by a complete or partial loss of lustre is referred to as "blooming" or "hazing." It occurs only after complete drying of the film, under the influence of moisture or high humidity. A permanent type of bloom occurs in certain varnishes which are characterized by good water resistance and a tendency to swell in contact with water. A temporary form of bloom occurs in the presence of ammonium sulfate; it is removed by rubbing with a damp cloth.

Oil and resin mediums are complex organic substances that deteriorate in elaborate ways; while oils sometimes bleach in the light, resins tend to yellow.

Paint films and glazes containing vegetable oils slowly turn yellow-brown when placed in darkness. Glazes containing verdigris in resin mediums have turned brown from exposure, but were discovered to be brilliant and clear in areas protected from light.

6.0 BIBLIOGRAPHY

- Broadnax, Frank.** 1977. "Spots on Furniture and Woodwork," *Old House Journal*, Vol. 5, No. 6 (June), p. 2.
- Hamburg and Morgans.** 1979. *Hess's Paint Film Defects*. Chapman and Hall, London.
- Jennings, S.J., and G.C. Rothery.** n.d. *The Modern Painter and Decorator*. Caxton Publishing Company Limited, London, pp. 133-51.
- Lowndes, W.S.** 1928. "Varnish Troubles" in *Painting and Interior Decoration*. International Textbook Company, Scranton, PA, p. 94.
- Mora, P., L. Mora and P. Phillipot.** 1984. *The Conservation of Wall Paintings*. Butterworths, London.
- Stanek, E.J.** 1978. "Refinishing" in *Antiques and Art*. Wallace-Homestead Book Co., Des Moines, p. 133.
- Vanderwalker, F.N.** 1925. *House Painting Methods*. Frederick J. Drake & Co., Chicago.
- Weeks, K.D. and D.W. Look.** 1982. "Paint on Exterior Historic Woodwork," *Technology & Conservation*, Vol. 7, No. 2, pp. 34-45.

Illustrations are the property of the Heritage Conservation Program, unless otherwise noted.

VOLUME VI

CONSERVATION OF MATERIALS

7.3

PAINT

ANALYSIS

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: ANNA KOZLOWSKI

CONTENTS

1.0 INTRODUCTION

2.0 PRESERVATION OF PAINT EVIDENCE

3.0 SEQUENCE

3.1 DETERMINING FINISH COATS

3.2 EVIDENCE OF PAINT REMOVAL

4.0 ANALYSIS OF COMPONENTS

4.1 PIGMENT

4.2 BINDER

5.0 LIMITATIONS OF A QUANTITATIVE ANALYSIS

5.1 COLOUR

5.2 TEXTURE

5.3 DEGREE OF TRANSLUCENCY

5.4 GLOSS

6.0 DECORATIVE PAINTING

7.0 BIBLIOGRAPHY

1.0 INTRODUCTION

The lack of understanding of the mechanisms of paint deterioration and the prohibitive expense of sophisticated scientific investigation can lead to the destruction or misinterpretation of the remaining physical evidence of period surface finishes.

The purpose of this article is to provide background information about paint analysis considerations other than colour identification (see Vol. III.10.2). It is intended to be used by professional and technical personnel who conduct analytical investigations of historic structures.

2.0 PRESERVATION OF PAINT EVIDENCE

Successive layers of paint finishes form an irreplaceable record of the evolution of painting practices and of the changes in popular taste.

Samples of paint, cut out, labelled and preserved at low temperature in the dark or sealed in glass tubes filled with an inert gas, cannot substitute for the preservation of finishes in their original location. Many characteristics of old finishes, such as texture, patterns of discolouration and decorative motifs need to be examined at a large scale and in the various micro-climates that would have affected them.

3.0 SEQUENCE

Accumulated layers of paint or varnish can be exposed by cutting a shallow level through all the layers, down to the substrate, using a surgical scalpel. The incision can then be polished and examined under a microscope.

Alternatively, the finishes can be removed layer by layer using appropriate solvents.

3.1 DETERMINING FINISH COATS

Films of dirt in the cross section of layers indicate that the layer immediately below the dirt was exposed to the atmosphere for a period of time, prior to the application of a subsequent layer, and would have been a finish coat.

Those layers immediately adjacent to the finish coat may fracture off easily, because of the use of a glaze or varnish as the finish coat or the accumulation of dirt, resulting in poor bonding.

Finish glazes or varnishes applied over decorative painting, are discernible as transparent layers with some pigment content. However, they tend to be thin and may be difficult to identify through cursory visual examination at low magnification.

The priming coat on woodwork is recognized in cross section by its deep penetration into the pores of the wood. Sometimes it consisted of white lead mixed with red iron oxide which coloured it pink or with lamp black which made it a light grey.

3.2 EVIDENCE OF PAINT REMOVAL

If the flat surfaces of the woodwork show fewer paint layers than in the crevices of adjacent mouldings, carvings or hard-to-reach surfaces, then there is a strong possibility that there has been paint removal at an earlier date. To confirm this, look for signs of scorch marks on the wood or its adjacent plaster, pock marks in the remaining paint resulting from heat or chemical action of the remover or dried remover in the form of a brown powdery layer usually found where it would have been easy for the worker to forget to wash it off.

4.0 ANALYSIS OF COMPONENTS

4.1 PIGMENT

Rough approximations of application dates for successive paint layers can be determined if the pigments it contains are identified and compared to their dates of introduction into Canada (or the specific region of Canada).

Pigments in the layer(s) of interest can be isolated and examined under a microscope by conservation laboratories. An X-ray diffraction analysis is one useful technique for studying the composition of historic paint.

(For a listing of pigments, their dates, characteristics, and some tests to which they will react, see Gettens and Stout, *Painting Materials*.)

4.2 BINDER

To distinguish between an oil-based medium, and whitewash or casein mediums, drop a fragment of paint into a solution of muriatic acid. Whitewash or casein will be totally dissolved, but the oil-based medium will not be affected. Distemper paint is dissolved by hot water. Shellac varnish is dissolved by denatured alcohol.

Advanced analytical methods exist in special conservation laboratories for examining binders:

- a. infrared spectrophotometry for analysing soluble resins found in spirit varnishes;
- b. thin-layer chromatography to identify constituents of oils, tempera, glue, casein, water-soluble gums and organic-soluble resins;
- c. gas chromatography to identify drying-oil binders; and
- d. long-wave ultraviolet radiation to distinguish between oil and proteinaceous layers.

5.0 LIMITATIONS OF A QUANTITATIVE ANALYSIS

An analysis of the constituents of an old paint finish does not, by itself, provide the formula for reproducing its original appearance. See also Vol. III.10.2 "Colour" and Section 7.1 "Composition and Properties: Oil-Based Paints" for additional discussion of investigating and reproducing period finishes.

5.1 COLOUR

A pigment's colouring power varies inversely with the size of the pigment particles; the more finely divided, the more effect the pigment has on the paint colour. The mixing of the pigment into the binder and thinner is called dispersion. For example, equal quantities of Prussian blue, when mixed with a given quantity of white lead, can produce either light greyish blue or darker bright blue, depending on how thoroughly the Prussian blue was dispersed.

Old paints were usually mixed by hand, resulting in poor dispersion of pigments which produced interesting and recognizable variations in colour. The action of brushing might produce streaks that would be partially blended by a cross-brushing at right angles to the first.

Pigments such as natural earths are composed of particles of many different sizes. Furthermore, they are frequently impure, consisting of particles of many varied colours. In many cases, the particles are large enough to be seen with the naked eye and impart a special quality to the painted surface.

5.2 TEXTURE

Old painted surfaces generally display brush marks because natural-oil mediums do not flow together as well as modern

synthetic paints. Brush marks were carefully aligned with the design of the features being painted; the results varied with the skill of the painter.

It must also be taken into consideration that successive coats could be pumiced smooth between applications. Frequently, a high quality paint job would call for four or more coats to achieve the desired finish.

5.3 DEGREE OF TRANSLUCENCY

Translucency can be achieved by a number of different methods. Some old oil-based paints tend to be slightly translucent, not only because of the increase in light transmission resulting from a rise in the refractive index of the aging oil, but also because of the use of chalk as an extender. Having an index of refraction close to that of oil, chalk admits light deeply into a paint film; when the light is reflected from within the paint, it gives the impression that the paint is a material, having thickness, rather than simply being a colour film.

5.4 GLOSS

Varying degrees and types of gloss were common in different periods. Examination of pigment-volume concentrations of period paint formulas will provide some indications.

Clear and coloured translucent glazes impart glossiness and deepen the ground colour. They provide protection from air, dirt, smoke and abrasion and they retard fading.

6.0 DECORATIVE PAINTING

Decorative painting (such as graining, marbling and stenciling) was extensively practised in the early 19th century. One can expect to find decorative work (or at least traces of it) applied to many of the original materials in a building of that period: painted floor boards may lie beneath layers of linoleum, grained woodwork beneath layers of paint or scenic murals beneath layers of wallpaper.

Care should be exercised in the removal of old wallpapers; decorative painting executed on plaster walls can be transferred to the back of the wallpaper.

7.0 BIBLIOGRAPHY

- Batcheler, Penelope Hartshorne.** 1968. *Paint Color Research and Restoration*. American Association for State and Local History, Nashville.
- Cawley, Frederick D.** 1978. *Property Owner's Guide to Paint Restoration and Preservation*. Preservation League of New York State, Albany, NY.
- Doonan, Nancy Locke.** 1982. "Historic Exterior Paints," *Bulletin of the Association for Preservation Technology*, Vol. 14, No. 2, pp. 26-30. Ottawa.
- Feller, Robert L.** 1976. "The Deterioration of Organic Substances and the Analysis of Paints and Varnishes." *Preservation and Conservation: Principles and Practices*. The Preservation Press, Washington, DC, pp. 287-303.
- Phillips, Morgan W.** 1976. "Problems in the Restoration and Preservation of Old House Paints." *Preservation and Conservation: Principles and Practices*. The Preservation Press, Washington, DC, pp. 273-86.
- Welsh, Frank S.** 1982. "Paint Analysis," *Bulletin of the Association for Preservation Technology*, Vol. 14, No. 4, pp. 29-30. Ottawa.

VOLUME VI

CONSERVATION OF MATERIALS

7.4

PAINT

INTERVENTION

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

CONTENTS

1.0 BIBLIOGRAPHY

1.0 BIBLIOGRAPHY

- Alderman, C.** 1984. "Recreating a 19th Century Paint Palette," *Bulletin of the Association for Preservation Technology*, Vol. 16, No. 1, pp 47-57. Ottawa.
- Barclay, R., R. Eames and A. Todd.** 1980. *The Care of Wooden Objects*. Canadian Conservation Institute, Ottawa.
- Batcheler, Penelope Hartshorne.** 1968. *Paint Color Research and Restoration*. American Association for State and Local History, Nashville.
- Broadnax, Frank.** 1977. "Refinishing Wood Floors," *Old House Journal*, Vol. 5, No. 14 (April), pp. 42-43. Brooklyn.
- Butz, Rick.** 1982. "Repairing Finishes: Two Ways," *Fine Woodworking*, No. 34 (May/June), pp. 92-94.
- Cawley, Frederick D.** 1978. *Property Owner's Guide to Paint, Restoration and Preservation*. Preservation League of New York State, Albany.
- Curtis, John Obed.** 1980. "How to Save That Old Ceiling," *Old House Journal*, Vol. 8, No. 10 (Oct), p. 131. Brooklyn.
- Flaherty, Carolyn.** 1979. "Sand Paint," *Old House Journal*, Vol. 7, No. 9 (Sept), pp. 104-6.
- Herman, Dr. Frederick.** 1981. "Refinishing Floors," *Old House Journal*, Vol. 9, No. 2 (Feb), p. 27.
- Hodkinson, Jan.** 1979. "Conservation and Transfer of an Early 19th Century Painted Room," *Bulletin of the Association for Preservation Technology*, Vol. 14, No. 1, pp. 17-36. Ottawa.
- Labine, Clem.** 1976. "Dealing with Calcimine Paint," *Old House Journal*, Vol. 4, No. 5 (May), pp. 2-3.
- _____. 1984. "Don't Paint It-Wash It!" *Old House Journal* (August-September), pp. 142-43.
- Martin, Gina.** 1973. "Stencilled Wall Designers," *Bulletin of the Association for Preservation Technology*, Vol. 5, No. 2, pp. 63-65. Ottawa.
- Matero, Frank G.** 1983. "A Rare Example of Early 19th Century Trompe L'Oeil Decoration," *Bulletin of the Association for Preservation Technology*, Vol. 15, No. 3, pp. 34-38. Ottawa.
- Mehn, Daniel J.** 1977. "Floor Refinishing - A Practical Alternative," *Old House Journal*, Vol. 5, No. 8 (August), pp. 89-92. Brooklyn.
- Mora, P., L. Mora and P. Philippot.** 1989. *The Conservation of Wall Paintings*. Butterworths, London.
- Phillips, M.W.** 1971. "Discoloration of Old House Paints: Restoration of Paint Colors at the Harrison Gray Otis House, Boston," *Bulletin of the Association for Preservation Technology*, Vol. 3, No. 4, pp. 40-47. Ottawa.
- _____. 1982. "A Stone Porch Replicated in Wooden Blocks: The Morse-Libby House," *APT Bulletin*, Vol. 14, No. 3, pp. 13-21. Ottawa.
- _____. 1983. "Acrylic Paints for Restoration: Three Test Applications," *APT Bulletin*, Vol. 15, No. 1, pp. 3-13. Ottawa.
- _____, and **B. Powell.** 1982. "Several Experiences Using Lime Paste as a Cleaning Agent for Oil Paint," *APT Bulletin*, Vol. 14, No. 2, pp. 30-34. Ottawa.
- _____, and **N. Weiss.** 1975. "Some Notes on Paint Research and Reproduction," *APT Bulletin*, Vol. 7, No. 4, pp. 14-19. Ottawa.
- Saderstrom, Goran.** 1959. *Lime Paint On Facade*. The National Swedish Institute for Building Research, Stockholm.
- Stanek, Edward J.** 1978. *Antiques and Art*. Wallace-Homestead Berk Co., Des Moines.
- Weaver, M.E.** 1981. "New Paint and Old Distempers," *Canadian Heritage*, (December), p. 43. Ottawa.

Weeks, Kay D., and David W. Look. 1982. "Paint on Exterior Historic Woodwork," *Technology and Conservation*, Vol. 7, No. 12, pp. 34-45. Boston.

Wells, Joan. 1982. "Renewing a Marbleized Mantel," *Old House Journal*, Vol. 5, No. 6, p. 126. Brooklyn.

Welsh, Frank. 1976. "A Methodology for Exposing and Preserving Architectural Graining," *APT Bulletin*, Vol. 8, No. 2, pp. 70-75. Ottawa.

_____, and **Charles L. Granquist.** 1983. "Restoration of the Exterior Sanded Paint at Monticello," *APT Bulletin*, Vol. 15, No. 2, pp. 3-11. Ottawa.

Zucker, Howard. 1975. "How to Grain Like a Professional," *Old House Journal*, Vol. 2, No. 6 (June), pp. 1, 8-11. Brooklyn.

_____. 1975. "Glenview Sictorian Stencilling Restored," *Old House Journal*, Vol. 2, No. 2 (Feb), pp. 8-11. Brooklyn.

VOLUME VI

CONSERVATION OF MATERIALS

8.1

WALLPAPER

COMPOSITION AND PROPERTIES

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022
ORIGINAL DRAFT: S. MYERS

CONTENTS

1.0 INTRODUCTION

2.0 THE PAPER SHEET

2.1 COMPOSITION

2.1.1 *Fibres*

2.1.2 *Sizing*

2.2 PROPERTIES

3.0 THE PAINT LAYER

3.1 PRINTERS' INKS

3.2 WATER COLOURS

3.3 DISTEMPER PAINTS

3.4 OIL PAINTS

3.5 COLOURED VARNISHES

3.6 PIGMENTS

4.0 SURFACE COATINGS

5.0 ADHESIVES

6.0 SPECIAL MATERIALS

6.1 FLOCKS

6.2 MICA AND METALLICS

6.3 RAISED MOTIFS

7.0 BIBLIOGRAPHY

1.0 INTRODUCTION

John Houghton, in *A Collection for the Improvement of Husbandry and Trade*, published in 1699, wrote

... a great deal of Paper is nowadays printed to be pasted upon walls to serve instead of Hangings; and truly if all parts of the Sheet be well and close pasted on, it is very pretty, clean and will last with tolerable Care a great while; but there are some other done by Rolls in long sheets of a thick paper made for the purpose whose sheets are pasted together to be so long as the Height of a Room; and they are managed like Woollen Hangings, and there is a great variety,... which are Cheap, and if kept from Wet, very lasting.

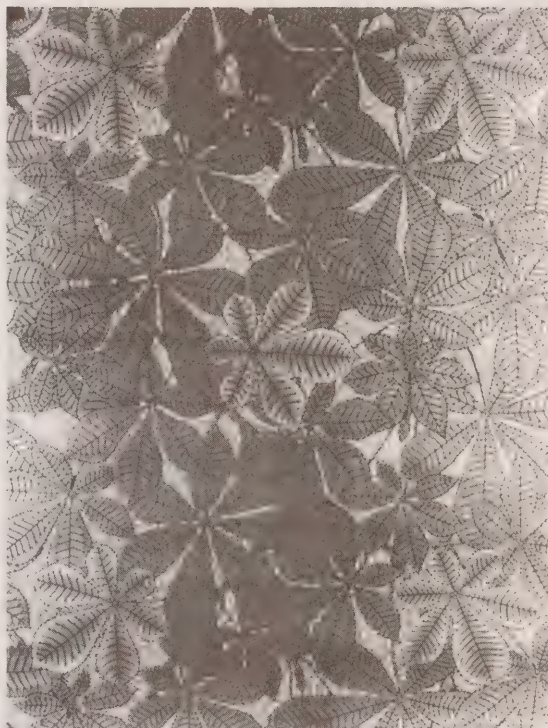
As his remarks suggest, wallpaper has been an important wall finish for over 300 years. The use of wallpaper extends back to at least 1509, the date of the "Cambridge fragments" found in England. Historic wallpapers are often not only very beautiful but also very important artifacts.

Wallpaper is a complex material with many layers: surface coatings, the paints or inks of the printed pattern, the paper layer supporting the paint, adhesives bonding the paper to the wall, and often lining papers or fabrics. It is also complex in its use and its status as an artifact. Wallpaper is a painting or print which serves as a wall finish and is an integral part of a building's construction. This complexity makes wallpaper not only difficult to analyse but also to conserve.

Very little has been written about the technical aspects of the composition or conservation of historic wallpapers. Most of the literature that does exist on the subject is in the form of case studies and is concerned with individual wallpapers. Therefore, information about the composition and properties of wallpaper must often be inferred from literature on paper as a printing material, paints in fine art painting and so on.

This article is an introduction to the materials of which historic wallpapers are composed and to the properties which are significant in their conservation.

Information on the deterioration, investigation, and repair of a historic wallpaper is contained in three articles in Sections 8.2 to 8.4. Excellent published sources include *Wallpapers in Historic Preservation* (Frangiamore 1977) and *Wallpaper in America* (Lynn 1980).



Colour Print from Wood Blocks, ca. 1877-80
Wallpapers. Oman and Hamilton. 1982.

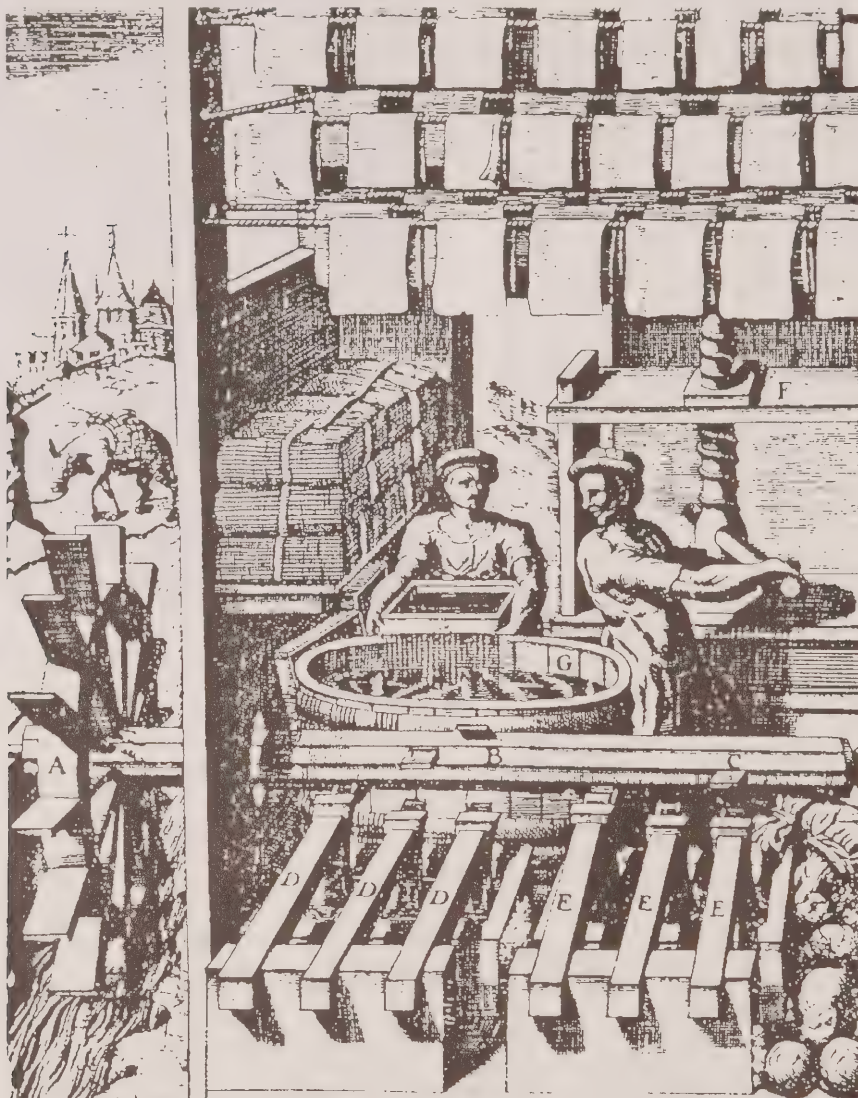
2.0 THE PAPER SHEET

Paper is a composite material, consisting of fibres interlaced to form a compact sheet. Until at least 1820, wallpaper was made with sheets of handmade paper.

The processes involved in making paper by hand are illustrated in the composite drawing of a German paper mill of about 1660. The rags, ropes, and other raw cellulose materials were first sorted and washed and then allowed to ferment. The rotted materials were worked by cams (C) fitted to the main shaft (B) which was turned by a water wheel (A). The beaten pulp from this process was kept in a vat of lukewarm water (G). The vat operator scooped a small quantity of pulp from the vat onto the wired surface of the bottom half of a mould, known as the frame. The top half of the mould, called the deckle, held the pulp mixture in place while the operator shook it to drain off the water. This shaking also caused the fibres of the pulp to intertwine and form a matted layer on the surface of the mould. The

vat operator removed the wet sheet from the mould by pressing a woollen felt against it. The operator then laid in a stack of alternating paper sheets and woollen felts. This stack, which was called a "post" and which generally consisted of 144 sheets

of paper, was compacted in a screw lever press (F) to remove additional water and to flatten the sheets. The sheets of paper were air-dried on ropes, then sized to prevent feathering of inks (Shorter, p. 14).



Drawing of a water paper mill, ca. 1660 (Printed originally in Georg Andreae Bockler, *"Theatrum Machinarum Novum,"* Nuremberg, 1662. From Shorter, 1971.)
Courtesy of The Society for the Protection of Ancient Buildings, London.

Technological developments brought changes to paper-making. In the 1740s the Hollander engine began to replace the older, slower method of rag pulping. It was followed by the introduction of bleaching with chlorine to salvage coloured rags, by experiments with waste paper and new raw materials to augment the rag supply, and by the introduction of steam power (Shorter, pp. 37-38, 55-65). The 19th century brought the first successful introduction of new fibres to paper, the introduction of various processes to prepare the new types of fibres for papermaking, and the first successful use of machines to make continuous lengths of paper (with the Fourdrinier machine, patented in 1799 and first made in 1805 in England).

Whether handmade or machine-made, however, paper continued to be manufactured from a pulp, produced by mechanical or chemical means from a variety of raw materials. The main constituents of paper are the fibres and sizings. Inorganic white pigments, particularly clay and calcium carbonate, are also used as fillers in papers intended for printing (Browning, p. 14) to increase the opacity and smoothness of the paper and to improve its printing quality.

2.1 COMPOSITION

2.1.1 *Fibres*

The fibres used in papermaking are almost all cellulose fibres. Cellulose is an amorphous carbohydrate polymer ($C_6H_{10}O_5$)ⁿ, made up of molecules of glucose condensed into long chains (Browning, pp. 19-22).

Cellulose fibres are derived from plants. Until 1800 the raw materials for paper were linen and cotton rags, ropes and other products from flax and cotton plants. Because these materials are nearly pure cellulose, they require little or no treatment other than the soaking and mechanical pulping described above. (Silk fibres are also occasionally found in rag papers.)

Other fibres introduced to paper during the 19th and 20th-centuries included straw (for low-quality papers), grasses (such as bagasse, bamboo, sabai and esparto), basts (fibrous barks) and wood. Esparto (most important of the grasses) became a common ingredient in paper after about 1860, and was still used in good quality wallpapers in Britain until a few years ago (Myers, p. 44). Wood became the most important of these introductions, however.

Raw wood contains cellulose, hemi-cellulose and lignin as well as various tannins, gums, oils and resins. The amount of non-cellulose material which remains in the paper pulp depends on the process used in its manufacture (mechanical, semi-chemical, chemical), on the type of process used for chemical pulps (for example, sulphate or sulphite) and on the bleaching treatment used after pulping (Browning, pp. 3-8).

Mechanical wood pulps also known as "groundwood" pulps are produced by a grinding of the de-barked wood (usually softwood) in water. Since only the water-soluble constituents of the wood are lost, the volume of yield is high (Browning, p. 7). The lignin which remains in the fibres is acidic, however, so papers made from groundwood pulp are brittle, weak and short-lived compared to linen or cotton rag papers. Mechanical wood pulps were used in paper-making after about 1848 in Germany, 1869 in Britain and 1875 in the United States. These pulps are still used in the production of inexpensive wallpapers.

Semi-chemical pulps (e.g. neutral sulphite semi-chemical, and semi-kraft) are produced by partially digesting the wood with chemicals before grinding and this digestion removes some of the lignin content. They involve a less complete digestion than the full chemical processes and remove less of the lignin. The semi-chemical processes were not developed until the 20th century (ca. 1926).

Chemical wood pulps are made by digesting wood chips with a cooking or pulping liquor which dissolves most of the ligneous binding material and allows separation of the cellulose fibres and an almost pure cellulose pulp. The most important chemical processes are the sulphite, modified sulphite, sulphate and soda processes (Browning, p. 4). Bleaching processes were also developed to remove residual lignin and coloured materials from the chemical pulps.

The earliest chemical wood pulps were produced with the soda process, which was operated on and off from 1845 to 1869, with a solution of caustic soda being used to digest the wood chips. The technical problems of bleaching and prevention of blackening were so great, however, that the process was little used, and then mainly to produce wrapping papers, until the "bleached Kraft" process was developed in about 1930 (Grant, pp. 10-11). Improvements in the chemical treatment of wood pulps brought the sulphite process, commercially viable from

the 1870s, and then the sulphate process, commercial after 1884 in Britain and about 1907 in North America. The sulphite pulp was cooked in a liquid containing calcium bisulphite with an excess of free sulphurous acid, so it is easy to see why these early wood pulp papers were so acidic and weak, and were used only for inexpensive wallpapers meant to be shortlived. Modifications to the sulphite process and the introduction of sulphate pulps brought great improvements, however, and by the early 20th-century wood fibre papers could be produced without the problem of acidity.

Almost no specific documentation exists concerning the fibres used in making wallpapers, so more general references concerning the development of paper-making technology and materials must be consulted. For references which summarize the dates of new introductions, see Section 8.3, especially 3.2, which discusses the analysis of paper fibre.

2.1.2 Sizing

Other than cellulose fibres, the main constituents of the paper used for wallpapers are sizing materials. The most common sizing materials are rosin, starch and glue (Browning, p. 14). Sizing provides resistance to the penetration of water and printing materials, preventing feathering of inks and paints. Sizings are also used to strengthen paper and to give it a smooth surface.

Internal sizes are those added to the liquid paper pulp during the manufacturing process. They may also be called "engine" or "beater" sizes.

Surface sizes are those applied to the surface of the paper after it has been made. These are applied by dipping the paper in a size tub, either in a separate operation or within the dryer section of the paper-making machine (which may be called tub sizing), or with a size press on the paper-making machine (Browning, p. 83).

Rosin is almost always used as an internal size and is used to prevent feathering. Rosin is found in German papers after about 1800 and others after about 1805 (Grant, p. 19). It is a solid resinous material obtained from the wood or resin of pine trees and is composed mainly of resin acids. The rosin content of paper usually varies from 0.5 to 4 percent of the weight of the paper (Browning, pp. 71-73). Like other resinous substances, rosin is a harmful addition to paper – with time, it becomes dark and brittle. Also harmful to the permanence of the paper is the alum which is used with rosin sizes to precipitate the rosin onto the cellulose fibres.

Starches have been used to size paper since at least 312 A.D. and are used for both internal and surface sizing. When used as an internal size, starch increases the strength and smoothness of the paper but does not greatly affect its water and ink resistance. When used as a surface size, starch is usually modified by various processes to lower its viscosity (Browning, pp. 82-83).

Starches are carbohydrates, $(C_6H_{10}O_5)_n$, occurring in plants as granules which vary in size and shape from plant to plant. Starch is very difficult to dissolve in cold water, but when a starch-water mixture is heated, the starch granules swell and form a gelatinous solution that sets to a jelly as it cools, producing a smooth hard surface (Gettens and Stout, p. 63).

Glue, or its purer form gelatine, is used as a surface or "tub" size and has been used for sizing paper since about 1350. Handmade paper which was to be printed was traditionally dipped in a tub of size and dried before printing. The glues used in tub sizing are chiefly animal glues, which are complex proteins obtained by hydrolysis of animal materials such as hides and bones. When heated, glue can be dissolved in water to produce a hard, smooth surface (Browning, pp. 93, 192). Alum was also used as an additive in glue sizes.

There are some indications that sizing was not considered necessary for wallpaper when the paints being used had a glue/gelatine medium (see Lynn, 1981, p. 62). Tests conducted by Andrea Gilmore on twenty wallpaper samples dating from about 1790 to 1925 and printed with distemper paints indicated that the papers were not heavily sized, and that starch and rosin were the sizes used (Gilmore, pp. 9-10). However, sizing can be very difficult to detect.

Twentieth-century wallpaper is well sized so that it will retain its strength while being pasted and applied (Libby, p. 43). This would also have been an important requirement for historic wallpapers.

2.2 PROPERTIES

The properties of different papers vary considerably, depending on their condition and the way in which they were manufactured. The constituents and process of manufacturing of the paper can be varied to provide the qualities desired – for example, strength and folding resistance in paper to be used for children's books, or smoothness and resistance to inks in writing papers.

Paper is mainly cellulose-type fibres cast together in a felted structure. Generally, the longer the fibres are, the more they will be interlaced and the more resistant to damage the sheet will be. The length of the fibres and the degree of interfibre bonding vary mainly with the type of raw material used and the extent to which the fibres are beaten during the paper-making process. Beating, in general, increases interfibre bonding and therefore increases tensile strength, burst strength and density of the paper: while it decreases tear resistance (greater bonding of the fibres usually decreases the ability of the sheet to withstand tearing). While different papers have very dissimilar properties, some of the basic properties of paper are of interest when considering wallpaper.

The most important property of paper, when used as wallpaper, is that it is hygroscopic – it absorbs moisture from the air and gives off moisture again when the relative humidity decreases. When the relative humidity changes, paper takes up or gives off moisture fairly quickly until it reaches a balance with the relative humidity of the air. Its moisture content at that balance is the “equilibrium moisture content,” and is generally five to seven percent at a relative humidity of 45 percent (Reed, p. 17). As water is absorbed, the paper fibres swell, and they swell far more in diameter than in length. When soaked with water, wood paper fibres increase about 30 percent in diameter, and only one or two percent in length (Reed, P. 2). The moisture content of paper may be almost zero in very dry air or as much as 30 percent in air which is almost saturated.

A second basic characteristic of paper is grain. Handmade papers have randomly aligned fibres, and an absence of grain. The fibres in machine-made papers, however, tend to be aligned in one direction; the direction in which the pulp travels on the paper-making machine. To prevent excessive alignment, the wire screen of the machine is given a cross-wise shake. The extent of grain varies with the speed at which the machine is run and other factors, but grain is a characteristic of all machine-made papers. The effects of grain on the properties of paper are that:

- a. paper tears more easily in the grain direction than across the grain;
- b. paper is stiffer and stronger in the grain direction; and
- c. paper expands and contracts more in varying humidities in the cross-grain direction than in the grain direction (Reed, p. 13).

Another property of paper is its density or its relative hardness and lack of porosity. Dense papers are made from strongly beaten or hydrated pulp and are compact, with strongly bonded fibres. Moisture changes cause dense papers to expand and contract as a whole, and result in relatively large dimensional changes in the paper sheet (Reed, p. 14). Wallpapers, however, are made with relatively soft, porous papers whose fibres have not been strongly beaten (Clapp, pp. 68-71). Their fibres can therefore swell or shrink more without causing as much change in the overall dimensions of the paper.

A further characteristic of paper is that it loses almost all of its strength when wetted with water (for example, excessive moisture from a leaking wall). Different types of paper vary slightly in their loss of strength. Soft, porous, lightly beaten papers may retain only three to four percent of their strength when wet, while hard, dense sheets may retain up to 10 percent. The loss of strength is caused by swelling and weakening of the interfibre bonds of the cellulose fibres, not by weakening of the cellulose fibres themselves (Libby, p. 122). Wetting with organic liquids, such as alcohols, causes much less weakening than wetting with water.

3.0 THE PAINT LAYER

The paints which provide the pattern on wallpapers are composed of pigments (solid colouring matter) dispersed in a medium (liquid binding material). Individual pigments and media have very different characteristics. The main types of paints used in the production of wallpaper have been printers' inks, water colour paints, distemper paints, oil paints and coloured varnishes. The other major pattern material, flock, is described under “Special Materials” in 6.1 below.

3.1 PRINTERS' INKS

Printers' inks were used in the earliest printed wallpapers, from the beginning of the 16th-century to the mid-18th-century, and then largely superseded by the development of distemper paints. In stencilled wallpapers, inks were normally used to print the outline of the pattern, prior to stencilling. Early inks used for printing were usually black, and were made by grinding carbon pigments in a medium of oil, gum, gelatine or varnish (Plenderleith and Werner, p. 68). Carbon is a very stable pigment, unaffected by light, air, acids and alkalis (Gettens and Stout, p. 103). The oils and tarry matter in these inks may turn

brown on ageing, so that a brownish carbon ink may indicate age, but this is not always true (Grant, p. 34). The pigments used in coloured inks are less stable and are generally fugitive (Plenderleith and Werner, p. 70). Printers' inks may be water-soluble or not; their solubilities depend on the media which are used (see Section 8.3).

3.2 WATER COLOURS

Water colours have also been used from the beginning of wallpaper history for hand-painted and stencilled wallpapers. After the introduction of distemper paints, they continued to be used, mainly in the Chinese hand-painted papers. They are prepared by grinding pigments in water-soluble gums, usually gum arabic, and then mixing with water (Gettens and Stout, p. 77). Gums are thick plant juices; gum arabic is produced by the acacia tree. Water colour paints are generally thinly painted and somewhat transparent with a matte finish. Clearly, they are water-soluble.

Gouache is a term used to indicate a particular type of water colour paint, or gum tempera, also used on wallpapers. It is applied less thinly than water colour, and with mixed tints of white and colour rather than with transparencies of colour. The term is used more to describe the opacity of the paint than a difference of materials from water colours (Gettens and Stout, p. 27).

3.3 DISTEMPER PAINTS

Distempers were the most commonly used wallpaper paints from the middle of the 18th century to the early 20th century, for both grounds and patterns. Distemper paints contain a high proportion of pigment to medium, which gives them a porous surface layer and a matte or semi-matte finish (Mayer, p. 5). They tended to be applied thickly to wallpapers, and are opaque and chalky.

The term distemper is used to indicate a paint made with a protein medium, such as gelatine, glue or casein. Glue and gelatine are both prepared from animal bones, cartilage and skin. The difference between them is one of purity, glue being the more impure form. In painting, the term "size" is used to mean a nearly pure gelatine, and old distemper recipes sometimes refer to pigments being mixed with size. Casein medium is prepared from skim milk and lime or from powdered casein and ammonia. Vegetable glue prepared with caustic soda and

rosin was an inferior type of binding medium used in English wallpaper production (Bosshard-Van der Bruggen, p. 10). Fish glue (isinglass, made of the air bladders of the sturgeon [Penn, p. 26]) from Russia was very expensive, and so was used only for the finest colours (Bosshard-Van der Bruggen, p. 10). According to a 1796 edition of Robert Dossie's *Handmaid to the Arts*, published in England in various editions from at least 1758, gum arabic was used with size in the medium of some distemper paints. Dossie states that the gum, because of expense, was used only sparingly in making paints for grounding (see Lynn, pp. 60-61).

Because of the glutinous medium, many distemper paints are soluble in water. Glue and gelatine soften and swell in cold water, and dissolve in water when heated. Casein is insoluble in water and alcohol, but soluble in ammonia (Gettens and Stout, pp. 7-9, 25-26).

From the mid-18th-century, distemper wallpapers were almost always "grounded" – that is, one or more preliminary coats of paint were applied over the full surface of the paper to give a background colour before the pattern was printed. The paints used for grounds were also distempers, but they tended to have a high chalk content. Chalk was used as an extender in the whiting which made up a large part of white and pale-coloured distempers. Clay also became an important extender in wallpaper paints by the late 19th century (Lynn, 1981, p. 65).

3.4 OIL PAINTS

Period oil paints were made with a drying oil medium, most commonly linseed oil. They tend to have a glossy finish, due to excess oil medium which collects on their surface (Mayer, p. 5). They were known to dry slowly, as the oil absorbed oxygen. Oil paints were used on wallpapers occasionally for glossy accent colours. They were also used during the 19th century in attempts to make washable wallpapers (see also Section 7.1 in this volume).

3.5 COLOURED VARNISHES

These were used for both grounds and patterns on some of the more expensive wallpapers from the mid-18th century, and in 19th-century washable wallpapers. Their mediums were usually spirit varnishes, made by dissolving soft natural resins in alcohol. Shellac is the most common type of spirit varnish. Coloured varnishes have a smooth, glossy, translucent appearance.



"Willow," from Morris & Co. Pattern Books
Wallpapers, Oman and Hamilton. 1982.

When a spirit varnish is brushed onto a surface, the solvent evaporates, leaving the resin behind. Spirit varnishes have the advantage of drying quickly, but they often dry to a brittle, easily cracked surface.

Oleo-resinous varnishes made with turpentine, however, are apparently more pliant and less likely to flake (Penn, p. 28). Robert Dossie, in the 1796 edition of *Handmaid to the Arts*, recommended only turpentine varnishes for use on wallpapers, and gave directions for making such a varnish:

"Take of white resin half a pound, of sandarac and mastic each four ounces: Powder them, and then add two pounds of oil of turpentine, and place the bottle in which the mixture is put in a warm place, where it must remain till the resins, &c. be perfectly dissolved. The varnish may be rendered thinner, where necessary, by increasing the proportion of the oil of turpentine" (Lynn, 1981, p. 61).

Varnishes made with turpentine as the solvent, are sometimes called essential oil varnishes. Whitish (or colourless) varnishes were required for making coloured varnishes, and the most colourless were sandarac and mastic, made from resins of the same names.

Varnish sometimes darkens when exposed to light. Spirit varnishes become brittle with age and tend to yellow. Sandarac becomes darker and redder with age, while mastic yellows and becomes fragile and fissured (Gettens and Stout, pp. 34, 55, 59 and 72-73).

3.6 PIGMENTS

A great variety of pigments can be found in period wallpaper paints. From the late-18th-century new pigments were discovered and used at an ever increasing rate. Pigments are found singly and in complex combinations.

The function of a pigment is to impart colour and to hide the underlying surface or to combine and react with other ingredients of the paint to provide desirable properties such as durability or flexibility. Most coloured pigments also require a white hiding pigment.

There are few references which deal specifically with the pigments used in wallpaper production, or their dates. References dealing with the use of pigments in painting in general must be consulted. However, Dossie (1796) did give a list of "...the colours proper to be used for the painting or colouring the paper hangings...." For a transcript of this and other references dealing with wallpaper paints, see "Colors and Other Materials of Historic Wallpaper" (Lynn).

Additional information about pigments used in wallpaper production is also available from 19th-century discussions about the poisonous effects of the arsenical pigments which were used. Sources of information about the dates when pigments were discovered and their physical and chemical properties are:

Harley, Rosamund D., Ph.D. 1983. *Artists' Pigments c.1600-1835*. 2nd edition. Butterworths, London.

Mayer, Ralph. 1957. *The Artist's Handbook of Materials and Techniques*. Viking Press, New York.

Gettens, R.J., and G.L. Stout. 1966. *Painting Materials*. Revised ed. Dover, New York.

Penn, Theodore Zuk. 1984. "Decorative and Protective Finishes, 1750-1850, Materials, Process, and Craft," *Bulletin of the Association for Preservation Technology*, Vol. 16, No. 1. Ottawa.

Harley's book *Artists' Pigments* also analyses the archaic colour names used by Dossie and relates them to modern nomenclature.

As might be expected, there was frequently a discrepancy between the date when a pigment was discovered and the date it came into common use. For instance, Chrome Yellow (PbCrO_4) was discovered in 1797, but its formula was not published until 1809, and not widely available until after 1820. Chrome Yellow was in common use in wallpaper manufacture by the mid-19th century. A later colour, "Artificial Ultramarine," was discovered in 1826 and its formula was published in 1828, but its earliest recorded use for wallpapers was in 1864 (Frangiamore, p. 7).

A characteristic of "lake" pigments (made from secretion from the lac insect) used until the mid-19th century is that they tend to deteriorate when exposed to light. Most pigments fade in light, but some darken and others change hue, particularly greens composed of blue and yellow mixtures. Some are far more sensitive to light than others, so that historic wallpapers do not give a uniformly faded appearance, but can be completely different in effect than they were originally (see also Vol. III.10.2).

4.0 SURFACE COATINGS

Surface coatings were applied to wallpapers in the past to protect water soluble mediums and fugitive pigments, and sometimes to make the papers washable. They were also used to provide the gloss and lustre often thought desirable in the late 18th and early 19th centuries.

The surface coatings used were usually varnishes and sometimes other forms of natural resins. One type of varnish which was used on wallpapers was oil (oleo-resinous) varnish, which was made by mixing one or more resins in a drying oil, usually linseed oil. The oil dries by reacting with oxygen in the air and polymerizes around the resin. These oil varnishes tend to be much darker than spirit varnishes and so were much less suitable as surface coatings. Varnishes were also used as the sticky base coat in flock wallpapers, but there the darkness of the oil varnish seldom presented difficulties.

5.0 ADHESIVES

A variety of adhesives have been used for hanging wallpapers. Flour pastes are the most common, although animal glues and wheat or rye starch pastes have also been used. Recently, various types of cellulose paste and synthetic glue have come into use.

The following is a recipe for traditional flour paste:

Good paste can only be made from good flour - wheat flour is best for the purpose. Take about 4 pounds of good white wheat flour and stir it into a stiff batter; then beat it free from lumps and thin down more or less, as may be required, with cold water. If the paste is not to be used for gilt papers (sometimes called 'metal' or 'gold' papers) add 2 ounces of powdered alum (the alum must not be used with gilts, as it turns these dark); also add, if wished, a little borax, copperas, or carbolic acid to prevent insects from eating through the paper. Having stirred the batter well, pour in water that is boiling (nearly boiling will not do). Give a few turns with the paddle, and then pour in the boiling water fast and stir rapidly until the paste begins to swell and thicken and to lose the whiteness of the flour. It is then cooked. Then, if necessary, thin with more water to make it spread easily. This paste may be used warm, but it will go farther if left standing until cold, by which time it will have become whiter (Jennings, p. 103).

Alum was a standard additive, used in pastes to prevent mould from growing on the paste and wallpaper before they had dried. Alum produced acidity in both pastes and wallpaper, which contributed to their deterioration. Dextrine was added to some flour pastes, to make them stronger (Jennings, p. 104), and sugar and rosin were also used as additives.

Starch pastes are not as strong as flour pastes, and were used less often. Anne Clapp gives directions for making wheat-starch paste, by soaking the starch in cool water and then heating (Clapp, pp. 92-93). Because it is free of nitrogen and sulphur, pure starch paste has very little effect on the pigments in paints (Gettens and Stout, p. 63), and was therefore recommended for use with wallpapers with "delicate tints" (Gilmore, p. 22).

Most traditional wallpaper pastes are water-soluble, particularly when heat is applied (normally by steaming). Old pastes have been found, however, which would not dissolve in water or even strong solvents. With age, pastes can become dry and brittle and lose their adhesive quality. Many pastes also become acidic.

6.0 SPECIAL MATERIALS

Many materials have been used in the production of wallpapers, to meet changing tastes and to achieve special effects. A few of the most important of these special materials are described in the following three subsections.

6.1 FLOCKS

Flock wallpapers are known to have been made since the 16th century. First produced in France and England, they became very popular in Europe during the 18th century, for use in important rooms. Flock wallpapers were made by applying the pattern in a sticky substance (usually varnish, but also glue or thick oil), and while this was still tacky, scattering fine particles of wool or sometimes silk over it. The flock could be pre-dyed or dyed in place. The grounds of flock wallpapers were sometimes coloured varnishes (Lynn, p. 50), but often distemper. In "double flock" papers, the paper was given a solid grounding of flock, and then the pattern was printed over in a second application of flock.

The appearance of old flock papers is often very different now than it was originally, since the colours of the distempered grounds were often highly fugitive and the dyes used for the flock were relatively stable. For example, the flock wallpaper in the "Prince Regent's Room" at Clandon Park, Surrey, was produced in red flock on a red distempered ground. This "ton-sur-ton" effect imitated damask hangings which were popular at that time (1735). Now, however, the colour has left the distempered ground and the wallpaper gives an effect of strong contrast.

6.2 MICA AND METALLICS

In the second half of the 18th century, a fashion for glittering wallpapers developed, in imitation of a popular type of silk material called "lustering" or "lustring" which had a glittering finish (Fowler and Cornforth, p. 135). This glitter was achieved on wallpaper by powdering the minerals talc and mica, both

shiny silicates, and scattering this powder onto a sized (glued) area, similar to the process of flock printing (Greysmith, p. 78). Mica continued to be used on some wallpapers through the 19th century. In the late 1870s "damask" and "drawing-room" wallpaper styles became very popular, using the contrast between a matt ground and a shiny print, or vice versa. These shiny areas were again produced with powdered mica on a sized ground. In 1885, a technique for achieving a softer effect was developed, by mixing more finely ground mica with a size, and applying the liquid mixture as a paint (Sugden and Edmonson, p. 184). Mica is a mineral composed of aluminum silicate with other silicates, such as potassium.

Fashionable wallpapers from the late 18th century were also sometimes decorated with metals in silver, gold and bronze colours. The actual material may have been a mixture of tin and copper (Greysmith, p. 75).

6.3 RAISED MOTIFS

In the 19th century, wallpapers which imitated materials such as decorative plasterwork and wood carving were popular. This popularity brought the development, at the end of the century, of wallcoverings which were actually patterned in relief. Some of these were made of paper and can technically be called wallpapers; others were in different materials, used in the same way as wallpaper and are generally included together. The two that were popular longest and became best known are Lincrusta Walton (or simply Lincrusta) and Anaglypta.

Lincrusta Walton was the first of these raised motif materials to be commercially successful. It was developed by Frederick Walton in England in 1877, 15 years after obtaining several patents for the invention of linoleum (with solidified linseed oil as its main ingredient). The new product was first named "Linoleum Muralis," being really a linoleum for walls, and then renamed Lincrusta Walton - Lin for linum (flax = linseed oil), Crusta for relief, and Walton for its inventor (Sugden and Edmonson, p. 250). It was introduced to the United States in 1879 and became a major wallpaper item there after 1882 when North American manufacture began (Lynn, p. 442). Lincrusta was thick, resilient and very hard wearing, and was made in lengths and hung like wallpaper with paste. It was originally produced with a heavy canvas backing, but this caused a tendency to pull off walls due to the weight, so it was replaced by a light waterproof paper backing after 1887 (Sugden and Edmonson, p. 251). Lincrusta was sold plain, for painting after hanging or coloured, and was sometimes very ornate.

Lincrusta was followed by many other proprietary products imitating relief materials. These included Tynecastle, Anaglypta, Cameoid, Salamander, Cordelova and, in lower relief, Lignomur and Leatherette. Anaglypta became the most popular of these.

Anaglypta was made from paper pulp embossed on a papermaking machine, and was first manufactured in Lancaster in 1888. It quickly became popular as a cheaper and only slightly inferior substitute for Lincrusta, being lightweight and durable, and it superceded Lincrusta for ceiling work (Sugden and Edmonson, pp. 253-54). Like Lincrusta, it could be obtained plain and painted after hanging or produced in more elaborate patterns in the factory. An elaborate Anaglypta paper can be found in the dining room of Eldon House, London, Ontario, as well as an ornate Lincrusta in the central hallway.



Wallpapers in Historic Preservation
Frangiamore. 1977. USDI.

Many raised motif wallpapers today are vinyl based. The continuation of these older types of wall coverings and the renewed interest in the use of wallpaper generally in Canada, have contributed to the availability of commercial examples of many special effects papers. Manufacturers are producing fairly accurate replicas of these and the traditional patterns using improved paints and adhesives.

7.0 BIBLIOGRAPHY

- Bosshard-Van der Bruggen, Veronica.** 1975. *Report: On the Conservation of Wallpaper from Maison 40 in Quebec City*. Conservation Division. National Historic Parks and Sites, Ottawa.
- Browning, B.L.** 1969. *Analysis of Paper*. Dekker, New York.
- Clapp, Anne F.** 1981. "The Examination of Winterthur Wallpapers and a Progress Report, April 1980, on a Group of Papers from the Fisher House, Philadelphia," *Journal of the American Institute for Conservation*, Vol. 20, No. 2 (Spring), pp. 66-73.
- Fowler, John, and John Cornforth.** 1974. *English Decoration in the Eighteenth Century*. Barrie & Jenkins, London.
- Frangiamore, Catherine Lynn.** 1977. *Wallpapers in Historic Preservation*. National Park Service. U.S. Department of the Interior, Washington, DC.
- Gettens, R.J., and G. L. Stout.** 1942. *Painting Materials*. Revised ed. 1966. Dover, New York.
- Gilmore, Andrea Madsen.** 1979. *Wallpaper Conservation for the Architectural Conservator*. Unpublished dissertation. Graduate School of Architecture and Planning, Columbia University, New York.
- Grant, Julius.** 1937. *Books and Documents, Dating, Permanence and Preservation*. Grafton, London.
- Greysmith, Brenda.** 1976. *Wallpaper*. Studio Vista, London.
- Jennings, A.S.** 1903. *Wallpapers and Wallcoverings*. The Trade Papers Publishing Co. Ltd., New York.
- Libby, C. Earl., ed.** 1962. *Paper*. Vol. 2. Pulp and Paper Science and Technology. McGraw Hill, New York.
- Lynn, Catherine.** 1980. *Wallpaper in America, From the Seventeenth Century to World War I*. W.W. Norton & Company, Inc., New York.
- _____. 1981. "Colors and Other Materials of Historic Wallpaper," *Journal of the American Institute for Conservation*, Vol. 20, No. 2 (Spring), pp. 58-65.
- Mayer, Ralph.** 1957. *The Artist's Handbook of Materials and Techniques*. Viking Press, New York.
- Myers, Susann.** 1981. *The Conservation of Wallpapers in Historic Buildings*. Unpublished dissertation. Institute of Advanced Architectural Studies, University of York, England.
- Oman, Charles C., and Jean Hamilton.** 1982. *Wallpapers*. Harry N. Abrams, Inc., New York in association with the Victoria and Albert Museum, London. Illustrations reprinted by permission: Courtesy of the Board of Trustees of the Victoria & Albert Museum.
- Penn, Theodore Zuk.** 1984. "Decorative and Protective Finishes, 1750-1850. Materials, Process and Craft," *Bulletin of the Association for Preservation Technology*, Vol. 16, No. 1. Ottawa.
- Plenderleith, H.J., and A.E.A. Werner.** 1971. *The Conservation of Antiquities and Works of Art*. 2nd edition. Oxford University Press, London.
- Reed, Robert F.** 1959. *What the Lithographer Should Know about Paper*. 2nd ed. Technical Bulletin No. 8. Lithographic Technical Foundation, Inc., New York.
- Shorter, A.H.** 1971. *Paper Making in the British Isles*. David and Charles, Newton Abbot.
- Sugden, A.V., and J. L. Edmonson.** 1925. *A History of English Wallpaper 1509-1914*. Batsford, London.

Illustrations are the property of the Heritage Conservation Program, unless otherwise noted.

VOLUME VI

CONSERVATION OF MATERIALS

8.2

WALLPAPER

DETERIORATION

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: S. MYERS

CONTENTS

1.0 INTRODUCTION

2.0 THE BUILDING

3.0 ENVIRONMENTAL FACTORS

3.1 RELATIVE HUMIDITY AND
TEMPERATURE

3.2 LIGHT

3.3 AIR CONTAMINANTS

3.4 PATTERN STAINING

4.0 INHERENT FACTORS

4.1 ACIDITY OF THE PAPER

4.2 ALKALINITY OF THE PAPER

4.3 PAINT LOSS AND DETERIORATION

4.4 SURFACE COATINGS

5.0 METHOD OF HANGING

6.0 BIOLOGICAL DETERIORATION

6.1 MOULD GROWTH

6.2 INSECTS

7.0 MAINTENANCE AND MANAGEMENT

8.0 BIBLIOGRAPHY

1.0 INTRODUCTION

Wallpapers are often damaged by soiling and wear caused by the human occupants of buildings. Damage also results from less obvious causes, however.

Historic wallpapers are complex artifacts. Essentially they are paintings on paper which serve as decorative finishes within buildings. Wallpaper is the weakest element of a building's walls and is therefore easily damaged by the deterioration and instability of other elements such as plaster, timber supports and foundations. It is also easily affected by environmental factors and by attack from moulds and insects. Deterioration is also caused by factors inherent in the wallpaper itself, resulting from the quality, characteristics and inter-relationships of the materials from which it is made.



Wallpaper Deterioration - Damage Caused by Hanging Paper Directly on Unfinished Boards

Wallpapers in Historic Preservation. Frangiamore, 1977. Courtesy USDI.

The following article is a brief description of the ways in which these factors contribute to the deterioration of wallpapers. Some of the factors described here seem self-evident. However, many wallpapers in historic buildings continue to suffer from obvious and preventable damage, even though paintings and furniture, which are clearly perceived as artifacts, may be carefully protected in the same buildings. See Section 8.1 for an introduction to the composition and properties of period wallpapers.

2.0 THE BUILDING

The most obvious factors which contribute to the destruction of historic wallpapers are those which affect the building as a whole, particularly moisture and structural movement.

Moisture in walls destroys the support for wallpaper by causing instability of masonry, rotting of laths and structural timber and crumbling of plaster. Moisture which penetrates through to the wallpaper itself causes the paper to swell and disintegrate and to delaminate from the supporting wall as adhesives are dissolved. Moisture also causes staining of the wallpaper, from the water itself and from dirt, rust and adhesives which are carried through the paper by the moisture. Excessive moisture also contributes to outbreaks of mould and insect attack.

Moisture in the walls comes from three main sources:

- a. rain and water penetration, from leaks in roofs, gutters, doors, windows, chimneys, exterior walls and plumbing pipes and fixtures;
- b. rising damp; and
- c. condensation of moisture within walls and roof spaces or on windows.

Structural instability causes cracks in the supporting walls and therefore in the wallpaper itself. In general, structural movement in the building may be caused by:

- a. the use of the structure (e.g. overloading of floors);
- b. vibration from road traffic or mechanical equipment;
- c. wind, rain or thermal movement; and
- d. the failure of some element of the building; shifting and settling of foundations, rotting in timber members, spreading of roof trusses and loss of bonding between inner and outer skins of masonry are some of the most common ways in which elements of the building fail.

The wallpaper is the weakest element of the wall construction. Structural movement causes wallpaper to tear, following cracks in the plaster or other substrate.

Historic wallpaper is very easily affected by moisture and instability in the building in which it is hung. Usually, the wallpaper must be removed from a room where these problems are discovered and not returned to it until after treatment is completed.

3.0 ENVIRONMENTAL FACTORS

The building environment can be very destructive to wallpapers. The wallpaper and its support are made up of layers: surface coatings such as varnishes, the paint layer on the surface of the wallpaper, the paper itself, adhesives, lining papers or fabrics, plaster, wood lath and so on. With changes in relative humidity and temperature, these layers all move in different ways and at different rates and even slight changes in the substrates can cause tearing in wallpaper, the weakest layer. In addition to this differential movement, the paint and paper layers of the wallpaper can themselves deteriorate through the destructive effects of relative humidity, temperature, light, air movement and air pollution.

3.1 RELATIVE HUMIDITY AND TEMPERATURE

The control of relative humidity has a significant effect on a wallpaper's stability, because paper is a hygroscopic material – it absorbs moisture from the air. Paper takes up or gives off moisture fairly rapidly until it comes to a balance (“equilibrium moisture content”) with the relative humidity of the air. At a relative humidity of 50 percent, paper has a moisture content between five and seven percent (Reed, p. 15). At high relative humidities (above 70 percent), this moisture content is greatly increased and the paper fibres are swollen and weakened. Relative humidities of 70 percent or more also allow destructive moulds to grow and encourage the presence of insects. At low relative humidities (below 30 percent), the paper fibres shrink and become brittle, leading to distortion and splitting. Fluctuations in relative humidity are particularly harmful, since they “exercise” the paper by causing it to repeatedly swell and contract, resulting in physical damage to paper fibres. Fluctuations in relative humidity and temperature also speed up the rate at which the paints of the wallpaper deteriorate (see 4.3 below).

The air in Canadian buildings tends to fluctuate in relative humidity with the seasons, being dry during the winter heating season and moist in summer when heating is turned off and the relative humidity indoors approaches that outside the building. Human activities such as cooking and clothes drying can add excessive moisture to the air at any time of year. Large numbers of visitors in a historic building can also raise the humidity considerably simply by breathing, and as a result of evaporation from damp clothing on rainy days.

Humidity control is related to temperature, because warm air can hold more moisture than cooler air. In the range of comfortable temperatures for humans within buildings, the relative humidity changes by about four percent for every one degree Celsius of temperature change.

Temperature is also related to deterioration of paper in more direct ways. Heat causes brittleness in paper and speeds up processes of chemical and photochemical degradation, as well as encouraging biological attack (Clapp, p. 17). The rates of chemical reactions are, as a rule of thumb, doubled for each 10°C rise in temperature (Phillips, p. 86).

Large changes in temperature and relative humidity will damage wallpaper and are increasingly destructive if the changes are rapid. Heat sources, such as radiators, placed near historic wallpapers can be particularly destructive, because of deterioration from heat and vapour, rapid changes in temperature and humidity as the heating turns on and off and currents of moving air that may cause soiling.

Internationally recognized ideal standards for average environmental conditions in relatively mild climates have been established for the conservation of environmentally sensitive artifacts, which would include historically important wallpapers. These ideal standards are:

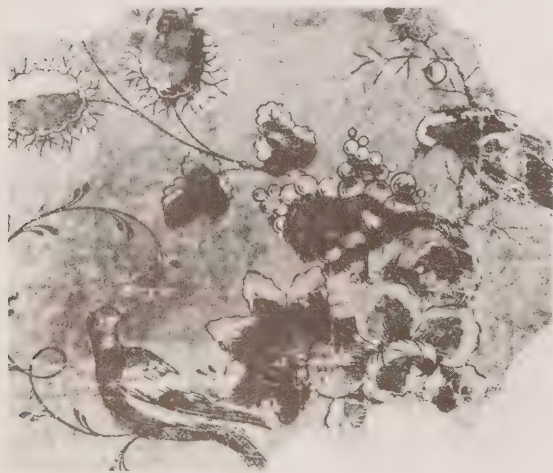
Relative humidity	47-53 percent, daily fluctuation not to exceed ± 2 percent.
Temperature	20-25 C°, daily fluctuation not to exceed $\pm 1.5^{\circ}\text{C}$.

These standards are useful in considering the conservation of small samples of historic wallpaper which are to be stored in a new museum. Clearly, however, such standards are impossible to achieve for wallpaper hung on the walls of most historic buildings. Also, relative humidities of around 50 percent at 21°C are too high for most historic buildings in Canada

during winter months. Attempts to reach such levels with older buildings would result in condensation problems in winter, and would lead to crumbling plaster, rotting wood, spalling masonry and other disastrous effects on building fabric. Excessive cooling of historic buildings in summer can also lead to condensation problems when relative humidity levels outdoors are very high (Phillips, p. 84).

More practical levels of environmental control are now being advocated for historic buildings. Early experience shows that summer highs of 65-70 percent relative humidity and winter lows of 30-35 percent are possible without damage to either the historic artifacts or the fabric of historic buildings (see Weaver, p. 4). For wallpapers, however, it is important to remember that conditions within a room can result in localized areas of higher humidity. Cool exterior walls, poorly ventilated areas behind furniture, and minute areas of dust, salt or iron particles can all result in localized relative humidities above 70 percent, allowing mould to grow, even though the general humidity in the room is well below that level (Clapp, pp. 15-16).

In deciding on environmental control for historic wallpapers, the importance and the condition of the wallpaper must be balanced against the ability of the building fabric to withstand environmental stress. Existing environmental conditions in the building must be carefully monitored before those conditions are changed.



Damaged Wallpaper, Kinderhook, NY

The Removal and Conservation Treatment of a Scenic Wallpaper, Paysage à Chasses, From the Martin Van Buren National Historic Site. Hamm & Hamm, 1981.

3.2 LIGHT

Light is also a factor in the permanence of wallpaper. Intense or prolonged lighting is harmful. While light is essential for the viewing and enjoyment of wallpapers, keep light levels low and do not expose historic wallpapers to light for long periods of time.

Both daylight and fluorescent light contain ultraviolet (UV) light. (Incandescent lighting gives off only very low levels of ultraviolet radiation.) Ultraviolet light causes photochemical degradation of the paper layer of wallpaper and results in discolouration, weakening and embrittlement. Paper discolouration depends on factors such as constituents of the paper; for example, pure cellulose bleaches in light while liquefied cellulose (for example, in groundwood pulps) becomes yellow (Clapp, p. 29). Ultraviolet light also affects the paint layer of wallpaper. Exposure to light, and particularly UV light, is a major reason for pigment deterioration. It causes photochemical changes which result in fading of some pigments and darkening of others. The media of the paint layer are also affected by strong light, which increases the rate of destructive oxidation (see 4.3 below). Strong light also speeds up the yellowing, hardening and embrittlement of coatings (varnishes) on wallpaper.

Both daylight and incandescent light contain infrared light, which causes heating of the paper, resulting in drying and embrittlement and possibly discolouration. Spotlights are particularly harmful, because of the great heat they produce. Strong infrared light can also cause the media of the paint layer to deteriorate through oxidation and can cause pigments to fade or darken.

The damaging effects of light are related to the quality of light source and the level and duration of illumination. Most harmful to wallpapers are the higher frequencies of the light spectrum, from ultraviolet through the violet and blue frequencies of visible light. Damage is directly related to the level of illumination and to the time of exposure – 100 lux of radiation for one hour can be expected to cause the same damage as ten lux for ten hours. The exclusion of ultraviolet light and the control of illumination to reasonable levels and durations are therefore the main considerations in preventing light-related damage to wallpapers (Plenderleith and Werner, pp. 13-15).

The level of illumination can be expressed in foot-candles (lumens per square foot) or in lux (lumens per square meter). One foot-candle is approximately equal to ten lux. For wallpapers of

historic value which are very sensitive to damage by light, 50 lux is the recommended (if not always achievable) level of light intensity (Lafontaine, p. 3). Wallpapers of historic value should not be exposed to more than 100 lux of light except for very short periods and even less important wallpapers should not receive more than 150 lux. A standard suggested for removal of UV radiation is that the proportion of UV radiation should be below 75 microwatts per lumen (Thomson, p. 6).

3.3 AIR CONTAMINANTS

Soiling of wallpapers is related to the building environment. Dirt, soot and oily particles in the surrounding air are drawn into the wallpaper by moisture or deposited on its surface by moving currents of air. These particles cause staining of both paints and paper. Soiling of wallpapers is accelerated by large amounts of dust and dirty particles in the air and by circulation of air in concentrated patterns, such as occur above radiators and at doors, windows, baseboards and other sources of draughts.

The air may also contain pollutants which harm wallpapers in other ways than by soiling. Air near the sea is often laden with water droplets containing minute amounts of salt, that may be deposited on the surfaces of walls and furniture within a room. The salt is hygroscopic and creates small areas of high relative humidity which encourage mould growth and other problems associated with dampness, even in rooms that are apparently quite dry (Plenderleith and Werner, pp. 11-12).

A more common problem is the presence in the air of atmospheric pollutants, particularly sulphurous gases from the burning of fuels. Hydrogen sulphide in these gases reacts with metals to form dark-coloured sulphides and is particularly damaging to paint films containing white lead. Sulphur dioxide in the atmosphere oxidizes readily to form sulphuric acid, which attacks a wide variety of materials, including paper. Nitrogen oxides in the air form nitric acid. Both sulphuric acid and nitric acid attack paper by hydrolysis, a reaction which weakens paper (see 4.1 below). Ozone in the atmosphere also damages wallpaper, causing the cellulose chain molecules of the paper to oxidize much more rapidly and therefore to break down.

3.4 PATTERN STAINING

Stains may show up on wallpaper where cold spots occur, for instance, at the locations of nails or between laths or timber framing members. This effect is known as pattern staining

and is a common problem with wallpapers that cannot be washed. Pattern staining results where an old exterior wall is climatically overstressed and a steep temperature gradient occurs across the wall in winter.

4.0 INHERENT FACTORS

The materials of the wallpaper itself are another factor affecting its permanence. The quality of the fibres used in making the paper is important, as is the extent to which fibres have been subjected to chemical treatments during the manufacture of the paper. Additives such as sizes can also contribute to the deterioration of the paper. For the paint layer, the media and pigments which are used and the ratio of pigment to binding medium are important factors.

The inherent factors affecting the deterioration of wallpaper are discussed below.

4.1 ACIDITY OF THE PAPER

Acidity is one of the main causes of paper deterioration and is such a general tendency that it seems to be a normal part of paper's aging. The way in which acidity causes paper to deteriorate has been described as follows:

Acidity causes loss of strength by hydrolysis of the cellulose molecules, a reaction which gradually breaks up their long-chain polymeric structure into fractions of low molecular weight. The reaction is progressive until in time, the scission of the molecular chains becomes so general that the once flexible, strong paper gets weak and brittle, allowing it to be torn even by the gentlest handling and completely split by folding (Clapp, p. 17).

The causes of acidity in wallpaper which are external to the paper include acids from:

- atmospheric pollutants
- mould growth
- acidic pastes used to hang the wallpaper
- backings such as wood or acidic lining papers
- acidic paints (especially green pigments containing copper compounds) and inks (especially iron gall inks) used to print the wallpaper

Causes of acidity which are inherent in the paper include:

- acidic materials such as acid-inducing iron or copper salts or particles embedded in the paper-making fibres during growth
- acids remaining in wood pulps after chemical treatments such as digestion and bleaching
- alum, which has been used as a sizing material from earliest paper-making to the present. Alum-hardened gelatin was an early size and, since the early 19th century, alum has been used in rosin sizes to precipitate the rosin and to give other desirable qualities to the paper-making pulp. In the resulting paper, however, alum reacts with water to form aluminum sulphates. Sulphuric acid is given off as a by-product. The acid combines with additional water to form an acidic solution between the paper fibres (Browning, pp. 155, 312). Note that the rosin used to size papers also harms them. While it does not contribute to their acidity, rosin becomes dark and brittle as it ages.
- impurities such as lignin which are found in the non-cellulose content of wood pulp.

Papers from all types of raw material become acidic, but the most seriously affected papers are those made since about 1860 with unpurified wood pulp and alum-rosin sizing (Clapp, p. 18).

The acidity or alkalinity of paper is expressed as a pH value. The pH value is explained by Plenderleith and Werner:

“An acid may be defined as a substance which forms hydrogen ions when dissolved in water and an alkali as a substance which forms hydroxyl ions when dissolved in water. Acids and alkalis are capable of neutralizing one another to form salts.”

pH is the hydrogen ion exponent and is related to the hydrogen ion concentration.

A solution in which the hydrogen and hydroxyl ion concentrations are equal is an exactly neutral solution and the pH = 7. In an acid solution the hydrogen ion concentration exceeds that of the hydroxyl ion and the pH is less than 7, whilst in an alkaline solution the reverse is the case and the pH is greater than 7 (Plenderleith and Werner, pp. 364-65).

Since pH values are logarithmic, a pH of 5.0 is ten times as acidic as one with a pH of 6.0. Paper is ideally neutral, with a pH of 7.0 but a range around neutrality from pH 6.5 to 8.5 is accepted as safe. Papers with a pH of less than 5.5 are usually treated to decrease the acidity, since otherwise the life of the paper will be greatly shortened. Treatment may also be desirable in much less acidic papers, particularly when other conservation work being carried out offers an opportunity for de-acidification.

4.2 ALKALINITY OF THE PAPER

Excess alkalinity is also occasionally a cause of deterioration in paper. When the pH rises above 9.0, there is a risk of oxidation of the cellulose (Plenderleith and Werner, p. 56). Cellulose in paper is normally oxidized slowly, but either alkalinity of the paper or ozone in the atmosphere causes greatly accelerated oxidation. Oxidation causes paper to become weak, as follows:

Oxidation leads to the formation of carbonyl (reducing) groups and of carboxyl (acidic) groups at one or more locations in the glucose units which comprise the cellulose chain molecule. Oxidation also results in the formation of peroxides, which contribute to further oxidation and side reactions....The formation of oxidation products may be accompanied by immediate scission of the polymeric chain molecule, or it may result in a sensitivity to further deterioration by a variety of influences (Browning, p. 32).

The materials usually causing alkalinity in paper are alkaline fibres such as calcium carbonate, casein in coatings and certain resins (Browning, p. 155). However, these are not often present in wallpapers in large enough quantities to cause alkalinity problems. Poorly controlled treatments to reduce acidity are the most probable causes of excess alkalinity in wallpaper. The strong alkalinity of fresh plaster can also damage wallpaper applied to it before it has had time to cure.

4.3 PAINT LOSS AND DETERIORATION

Paint loss can occur as the result of a number of external influences such as: dampness or rapid fluctuations in humidity and temperature, which cause loss of adhesion to the paper; insect activity and mould growth, particularly when the paints contain organic binders such as glue; and abrasion from surface dirt and from physical contact.



Paint Loss and Deterioration

Factors inherent in the paint also cause deterioration and loss. The physical and chemical processes of paint deterioration have not been as thoroughly investigated as those of paper deterioration and most of the research which has been done has concentrated on the oil paints and varnishes of fine art paintings. The deterioration of the distemper paints most commonly used on 18th- and 19th-century wallpapers is less well understood. Certain basic factors in their deterioration can be identified, however.

The media of wallpaper paints tend to suffer more deterioration than do the pigments. As explained by Gilmore:

The structure of paint – pigments encapsulated in a medium – suggests that the paint medium is more exposed to external forces of deterioration than the pigments. Paint media are also more chemically reactive than the majority of pigments and therefore [more] prone to deteriorative chemical changes. (Gilmore, p. 30)

The basic mechanism by which paint media deteriorate is oxidation. While oxidation is a natural aging process, the rate at which paint media oxidize is greatly increased by exposure to moisture, fluctuations in relative humidity and temperature and strong light. Oxidation causes paint media to yellow, shrink, become brittle and friable and change their sensitivity to solvents. This deterioration of the binding media leads to cracking, cupping and flaking of the paints.

In distemper paints, another inherent cause of deterioration is the high ratio of pigment to binding medium, which results in poorly bound pigments (Lee et al, p. 95). This can cause powdering, flaking and loss of paint. The manufacturing practice of placing heavy layers of distemper paints over very granular ground layers has also led to problems in bonding between the layers. Many 19th-century French wallpapers, such as the *Zuber et Cie* scenics, show characteristic cupping, cleaving and loss of paint for this reason (Hamm and Hamm, p. 118).

The pigments in wallpaper paints deteriorate mainly through fading resulting from an external cause – light (see 3.2 above). Some pigment deterioration also results from inherent factors. Some pigments (such as the chromates) change colour due to oxidation. Yellow lead chromate, for instance, reduces to green chromic oxide through oxidation (Gettens and Stout, p. 139).

Paints containing green copper pigments present special problems. Until the late 19th-century, few green pigments were available which provided the required colours, fastness, chemical stability and covering ability. Most of the greens used in wallpaper production were made with copper pigments, even though they were unstable and faded quickly. They included basic and neutral verdigris, malachite, Scheele's Green and Schweinfurt Green. Schweinfurt Green was often used in the 19th-century because of its bright colour, although it was an arsenical pigment and was known to be poisonous. The common use of copper-containing pigments continued up to the beginning of the 20th-century and they are still used in China today.

These green pigments are chemically unstable and their chemical reactions cause discolouration, ranging from small shifts of hue to a complete change to brown or black. They also cause acidity and brittleness in the paper adjacent to them. This can result in numerous small tears and perforations in the areas of green pigments. These copper-containing pigments and their chemical reactions which cause discolouration and destruction of wallpaper are discussed in an article by Professor Franz Mairinger (Mairinger et al).

One further inherent cause of deterioration is linseed oil, which was occasionally used as a binder in wallpaper paints. It causes severe degradation of the supporting paper (Hamm and Hamm, p. 171). Linseed oil is acidic, resulting in staining and embrittlement in paper to which it is applied.

4.4 SURFACE COATINGS

Varnishes are the surface coatings most often found on historic wallpapers. They are made with natural resins which streak and darken with age, giving the wallpaper a dark, dull appearance. They may also become brittle and, in cracking and shrinking, pull the paint layer off the surface of the wallpaper. A varnish coating may act as a vapour barrier and prevent evaporation of moisture from the wall, causing damage to the wallpaper, plaster and wood materials behind.

5.0 METHOD OF HANGING

The method used in hanging a wallpaper and the care with which it is hung are important influences on its later condition and stability.

Wallpapers deteriorate more rapidly when they are not lined with one or more layers of paper or fabric lining. The liners expand and contract with changing environmental conditions at the same rate as the wallpaper itself, buffer it against differential movement in the substrate, and also to a certain extent, against problems such as dampness in the wall. Good quality wallpapers were sometimes mounted directly on canvas or linen linings until about the mid-18th century, but the practice was abandoned because the paper tended to crack as it dried after hanging. Fabrics and paper respond in opposite ways to moisture absorption – paper expands and fabrics shrink. Canvas scrim did come back into use for wallpapers of the highest quality, but with one or more layers of paper lining applied over the canvas.

Mounting wallpapers over a substrate of wood (e.g. paneling) also leads to their degradation. The large dimensional changes in the wood caused by environmental conditions result in cracking and splitting in the wallpaper. Wood is also generally acidic when moisture is present and acids can easily travel from the wood to the wallpaper.

The flour and starch pastes traditionally used in wallpapers can contribute to their deterioration. They tend to be acidic and to cause acidity in the paper. Also, the pastes provide nutrients for moulds and insects, with resultant staining, acidity and other problems in the wallpaper.

Wallpapers hung with overlapping edges (rather than butted edges) tend to tear during large fluctuations in relative humidity and temperature, especially when the paper is dry and brittle. The overlapping edges, or overlapping edges in the lining papers behind, create lines of tension in the wallpaper (Hamm and Hamm, p. 171).

Wallpapers are known to last longer when hung away from the surface of the wall. The air space behind them provides ventilation and prevents water from soaking directly through to them.

6.0 BIOLOGICAL DETERIORATION

6.1 MOULD GROWTH

Moulds, which may also be called mildew, are minute saprophytic fungi capable of living on paper. They consist of tiny root-like threads called hyphae which felt together forming a mycelium. The mycelium throws up fruiting bodies that produce spores which are present in large numbers. Some types of mould live on the sizes, glues and pastes of the paint, paper and adhesive layers of wallpaper. Others live on the cellulose fibre itself.

When moulds begin to grow, a fine white fluff appears that soon forms visible furry patches of roughly circular shape. Action must be taken immediately, since moulds grow quickly once started and cause great damage to wallpaper. They damage paper by hydrolyzing the cellulose molecules, eroding the surface of the paper and making it brittle. They destroy sizings and the affected area of paper becomes weak and highly absorbent. They may destroy the paint layer, particularly when attracted by glue-based paint media. Severe mould attack can result in areas of complete loss of paint, while even milder infestations can cause deep discolouration. Moulds also increase acidity and local relative humidity. The rusty brown spots on paper commonly called foxing are the result of mould growth, although the mechanism by which foxing is produced is not fully understood.

In order to grow at room temperatures, moulds require nutrients, spores and humidity. Nutrients are provided by the wallpaper and spores are almost always present in a building. The controlling factor in mould growth is therefore humidity. Moulds flourish in damp, warm, unventilated conditions, and these may exist in some areas of a room (for example, in still air pockets behind furniture) even though the general relative

humidity is reasonably low. Mould may also grow on the reverse side of a wallpaper, where lack of ventilation produces greater humidity and where flour-based wallpaper pastes provide additional nutrients. This growth is eventually seen as staining on the face of the wallpaper.

6.2 INSECTS

Several types of insects attack wallpaper. The most common in Canada are silverfish and firebrats, cockroaches, booklice and carpet beetles. The damage to paper produced by silverfish is characterized by a pattern of paper loss which looks like fretwork or lace-like form with jagged edges (see Hughes). Wood-dwelling termites also attack wallpaper. Common furniture beetles and other wood-boring insects may damage wallpapers, in making flight holes to escape from woodwork.

Glue-based paint media, gelatine and starches in wallpaper sizings and pastes provide the most attractive nutrient for insects. Insects also damage the paper by eating the cellulose fibres. Destruction of sizings weakens the paper fibres, and consumption of cellulose fibres causes thinning or holes in the paper. Insects feeding on the paint media cause areas of paint loss. Booklice feed on moulds which grow on paper.

The greatest insect activity is associated with warm, dark, damp, poorly ventilated conditions. Insects often attack wallpaper from the back, so their presence is difficult to detect. Two common signs of insect activity are a scattering of small holes in the surface of the paper or adjacent wood and little piles of wood or paper dust on floors. Small pellets of insect droppings may also be found, corresponding in colour to the material on which the insects have been feeding. Droppings deposited behind a wallpaper may show through in places on the front of the paper. Other symptoms of insect infestation include moths themselves or the silk spun by a caterpillar when making a cocoon.

7.0 MAINTENANCE AND MANAGEMENT

The maintenance that a historic wallpaper receives can be very destructive. Wallpapers are often cleaned with abrasive or oily substances, causing loss of paint, shiny surfaces and staining. Wet cleaning damages water-based paints and also the paper. Vacuum cleaning with strong suction causes paint loss as well as damage to paper fibres. Vacuuming even with low suction is damaging to wallpapers which are in poor condition, such as those with flaking and friable paints and brittle paper.

Cleaning fluids and paints used on other surfaces in a room (such as painted mouldings) often splash and stain wallpapers. Stains from furniture polish on a wallpaper have been known to show the exact location and shape of the furniture placed against it.

Inadequate cleaning of the building in which a wallpaper hangs can lead to abrasion by dirt particles carried by strong air currents and by human contact. Poor housekeeping also contributes to pattern staining and to insect activity. Dust and cobwebs on the wallpaper also hold moisture against its surface. That moisture is often acidic due to atmospheric pollutants. Lack of conservation action, such as leaving loose, torn edges unattended, also leads to further damage.



Silverfish

Abrasion of wallpapers can be caused by tapestries, window drapes or paintings hung over them, by movement of furniture against them or by the activities of humans and pets. As well as abrading it, furniture arranged against a wallpaper decreases ventilation and prevents moisture from evaporating from its surface. This keeps the wallpaper damp and encourages mould and insects. Wallpapers are also often stained by food and drink, especially in dining rooms.

Wallpapers in historic buildings that are open to the public have additional problems. Heavy visitor traffic makes temperature and relative humidity more difficult to control. Unsupervised visitors tend to touch wallpapers, particularly unusual and valuable ones. Plexiglass panels are often placed over wallpapers to protect them in areas vulnerable to this type of soiling and abrasion. These panels themselves cause severe damage to wallpapers if they are not mounted away from the surface of the paper, because they prevent evaporation and hold soil against the surface. The requirements of lighting when rooms are open to the public cause more rapid fading and deterioration of wallpapers. Wallpapers are also very vulnerable to deliberate vandalism.

Repair and restoration treatments applied to wallpaper may also be destructive in the long term. Destructive treatments include coating with varnish, mending tears with adhesive tapes, mounting wallpaper on linings that have become highly acidic with time (such as kraft paper) and applying thick layers of overpaint.

Wallpaper is sometimes removed from walls and stored for long periods of time, because funds are not available for its conservation or because conditions are not suitable for its return to a building. A damp wallpaper which is moved to hot storage conditions can immediately develop mould growth and rapid drying in storage will cause cockling and paint loss. Rolling wallpapers for storage can lead to creasing and severe paint loss, particularly if they are rolled without a large-diameter core.

8.0 BIBLIOGRAPHY

- Browning, B.L.** 1969. *Analysis of Paper*. Dekker, New York.
- _____. 1976. *The Nature of Paper*. Deterioration and Preservation of Library Materials. University of Chicago Press, Chicago. Quoted material reprinted by permission: University of Chicago Press, Chicago.
- Clapp, Anne F.** 1978. *Curatorial Care of Works of Art on Paper*. 3rd revised ed. Intermuseum Conservation Association, Oberlin, OH. Revised 1987. Nick Lyons Books, New York. Quoted material reprinted by permission: Nick Lyons Books, New York.
- Gettens, R.J., and G. L. Stout.** 1942. *Painting Materials*. Dover, New York.
- Gilmore, Andrea Madson.** 1979. "Wallpaper Conservation for the Architectural Conservator." Unpublished dissertation. Graduate School of Architecture and Planning, Columbia University, New York.
- Hamm, Patricia, and James Hamm.** 1980. *Historic Wallpaper in the Historic Structure: Factors Influencing Degradation and Stability*. Conservation within Historic Buildings. Vienna Congress, IIC London, pp. 170-75.
- _____. 1981. "The Removal and Conservation Treatment of a Scenic Wallpaper, Paysage à Chasses, from the Martin Van Buren National Historic Site," *Journal of the American Institute for Conservation*, Vol. 20, No. 2 (Spring), pp. 116-25. Illustration reprinted by permission: American Institute for Conservation of Historic and Artistic Works. Copyright 1981.
- Hughes, A.W. McKenny.** 1952. "Insect Pests of Books and Paper," *Archives*, Vol. 7, pp. 19-22.
- Lafontaine, Raymond H.** 1981. *Environmental Norms for Canadian Museums, Art Galleries, and Archives*. Technical Bulletin No. 5. Canadian Conservation Institute, Ottawa.
- Lee, Mary Wood, Konstanze Bachman and Shelley Fletcher.** 1978. *Sauvages de la Mer du Pacifique: Treatment of an Early 19th Century Wallpaper Depicting the Voyages and Death of Captain Cook*. Preprints of Papers Presented at the 5th Annual Meeting of the American Institute for Conservation of Historic and Artistic Works, Boston, Mass., 30 May-2 June, 1977. AIC Preprints. American Institute for Conservation, Washington, DC.
- Mairinger, Franz, et al.** 1980. *The Destruction of Paper by Green Copper Pigments*. Conservation within Historic Buildings, Vienna Congress. IIC London, pp. 180-85.
- Phillips, Morgan.** 1981. "Wallpaper on Walls: Problems of Climate and Substrate," *Journal of the American Institute for Conservation*, Vol. 20, No. 2 (Spring), pp. 83-90.
- Plenderleith, H.J., and A.E.A. Werner.** 1971. *The Conservation of Antiquities and Works of Art*. 2nd ed. Oxford University Press, Oxford. Quoted material reprinted by permission: Oxford University Press, Walton, St., Oxford, OX2 6DP.
- Reed, Robert F.** 1959. *What the Lithographer Should Know about Paper*. 2nd ed. Technical Bulletin No. 8. Lithographic Technical Foundation, Inc., New York.
- Thomson, Garry.** 1980. *Some Hints on Measurement and Control of Climate in Historic Houses*. Conservation within Historic Buildings, Vienna Congress. IIC, London, pp. 6-8.
- Weaver, Martin E.** 1984. Unpublished draft of "Museums Operations Manual" (July). Ottawa.

Illustrations are the property of the Heritage Conservation Program, unless otherwise noted.

VOLUME VI

CONSERVATION OF MATERIALS

8.3

WALLPAPER

ANALYSIS AND REMOVAL

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: S. MYERS

CONTENTS

1.0 INTRODUCTION

2.0 DATING ANALYSIS

- 2.1 STYLISTIC CHARACTERISTICS
- 2.2 TAXATION STAMPS
- 2.3 MAKERS' MARKS
- 2.4 DESIGN REGISTRATION MARK

3.0 PAPER ANALYSIS

- 3.1 IDENTIFICATION OF HANDMADE AND MACHINE-MADE PAPER
 - 3.1.1 *Handmade*
 - 3.1.2 *Machine-made*
- 3.2 FIBRE ANALYSIS
- 3.3 SIZING ANALYSIS
- 3.4 pH MEASUREMENT

4.0 PATTERN ANALYSIS

- 4.1 APPLICATION OF PATTERN
- 4.2 PAINT ANALYSIS
 - 4.2.1 *X-ray Flourescence Spectrometer*
 - 4.2.2 *Infrared Spectro-photometer*
 - 4.2.3 *X-ray Diffraction*
 - 4.2.4 *Chemical Methods*
- 4.3 SURFACE COATINGS

5.0 SPOT TESTING

6.0 ENVIRONMENTAL FACTORS

7.0 RECORDING

8.0 REMOVAL

9.0 STORAGE

10.0 APPENDIX: FORMS

11.0 BIBLIOGRAPHY

1.0 INTRODUCTION

The analysis of wallpapers is a complex undertaking. Wallpapers are composed of many different layers and materials, which require different skills and techniques for analysis. Analysis is frequently undertaken in North America, however, because even small fragments of wallpaper can provide valuable information about the history of buildings and the changes and adaptations they have undergone.



Colour Prints from Wood Blocks – Late 18th to Mid-19th Century Wallpapers. Oman and Hamilton, 1982.

Wallpapers are commonly analysed for both dating and conservation purposes. Dating analysis is not within the scope of this article. However, dating and conservation analysis are difficult to separate, since the two often occur together and dating analysis helps to decide many conservation issues. The types of analysis common in dating wallpapers which are not also used

specifically in planning conservation treatments are therefore described briefly in 2.0 below.

Much of the analysis carried out on wallpapers must be done by a laboratory, which may or may not be one specializing in conservation. The person requesting the analytical work must give clear instructions about the type of information required from the analysis, in order for the lab results to be useful.

Removal of wallpapers is also a difficult and complicated task, made more so by the large areas involved. Removal techniques must be found which are less time-consuming than those used in working with fine art paintings. In some cases it may not be possible to remove wallpapers from their substrates or to separate the layers in a build-up of wallpapers, without destroying a large portion of the material. As well as technical challenges, removal of wallpapers involves philosophical questions which require clarity about conservation priorities and alternatives. The removal of any wallpaper, however fragmentary, from a historic building requires that recording be carried out prior to removal and that suitable storage conditions be provided for the wallpaper on removal.

This report presents a brief introduction to the subjects of wallpaper analysis and removal, and provides references for further study.

2.0 DATING ANALYSIS

Much of the accurate dating information concerning 19th- and 20th-century wallpapers is obtained through fibre and paint analysis, that is also used in analysing wallpapers for conservation treatment. The techniques used are described in 3.2 and 4.2 below. Important dating information, particularly useful with earlier wallpapers, can also be derived from stylistic characteristics, stamps and marks and the materials and patterns used.

2.1 STYLISTIC CHARACTERISTICS

A number of well-illustrated books are available on the history of wallpapers. These include the books by Eric Entwisle, Sugden and Edmonson, Oman and Hamilton, Brenda Greysmith and Catherine Lynn and a government report by Felicity Leung, listed in the bibliography of this report.

Accurate dating on the basis of stylistic characteristics is the job of an expert. Some of those who might be consulted are:

Miss Jean Hamilton, Senior Research Assistant
Department of Prints and Drawings and Photographs
Victoria and Albert Museum
Exhibition and Cromwell Roads
London SW7 2RL UK

Catherine Lynn
207 Pawson Road
Branford, CT 06405
U.S.A

Cooper-Hewitt Museum
Smithsonian Institution
9 East 90th Street
New York 10028
U.S.A

Felicity L. Leung
National Historic Parks
25 Eddy Street
Hull, PQ
K1A 0H3

The Cooper-Hewitt Museum has an extensive wallpaper reference collection, with slide index. Staff will send slide copies of specific types of wallpaper on request. For other wallpaper reference collections, see *Wallpapers in Historic Preservation* (Frangiamore, p. 55); "Wallpaper in Canada, 1600s-1930s," Vol. 1 (Leung, p. 395).

2.2 TAXATION STAMPS

Taxes were levied in Britain between 1712 and 1836 on paper made there that was to be used for producing wallpapers. After 1714, duty stamps were placed on the back of each sheet of paper or sometimes at the two ends of an assembled length or "piece" of wallpaper, when it had been counted for payment of duty. During the Georgian period from 1714 to 1830 the stamp was an interlaced "G.R." monogram surmounted by a crown, with the word "Paper" below. Various letters and numbers, as well as phrases such as "Duty Charged," were added to the stamps at times to prevent counterfeiting. Additional taxation stamps used during this period were:

- "First Account Taken" stamps: used after 1714 on each elephant-sized sheet of paper (58-60 cm wide by 70-80 cm long). The words were arranged in a circle around a royal crown.

- Frame Marks: stamped at both ends of an assembled "piece" after 1786. Frame marks consisted of a rectangular box with numbers and sometimes letters inside, including the year of production. Frame marks are very rarely found.
- Remnant Marks: applied to samples and small remnants.
- "W.R." stamp: this replaced the "G.R." monogram between the accession of William IV in 1830 and the repeal of duties in 1836 (see Longfield, pp. 91-116).

These taxation marks show that a paper was made in Britain between 1714 and 1836 and may narrow the date further. However, their absence can certainly not be taken to indicate that a paper is not of this origin or period. Record and report any taxation marks found to Jean Hamilton at the Victoria and Albert Museum, to help in the much-needed study of taxation marks. For a fuller discussion of taxation stamps, see Ada Longfield Leask's papers listed in the bibliography.

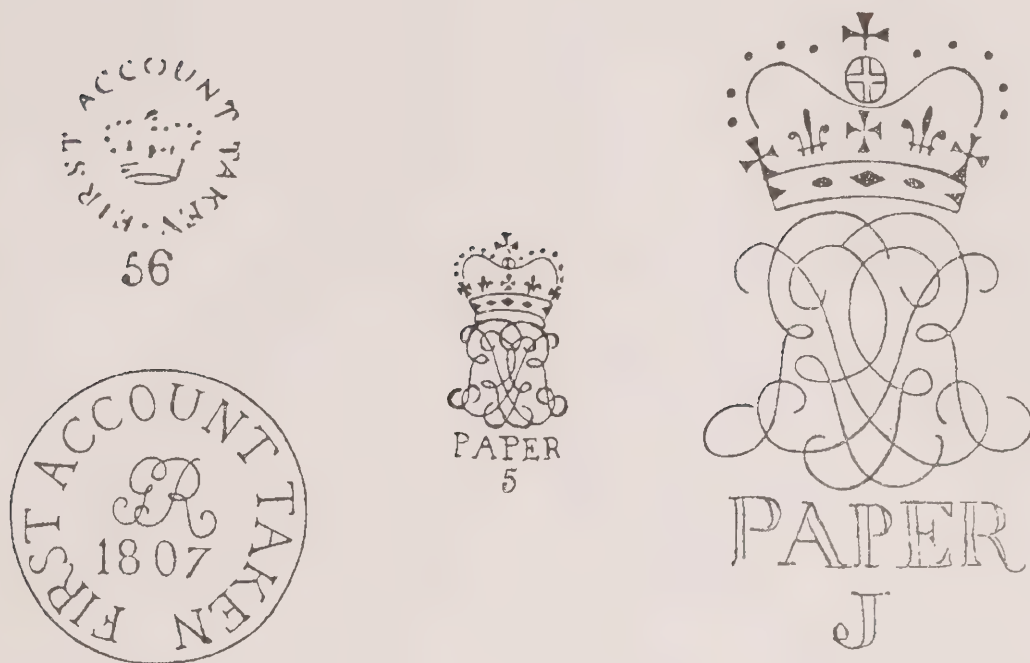
2.3 MAKERS' MARKS

Some wallpapers are known to have been marked with their maker's name from the beginning of wallpaper production, but such marks are rarely found on early papers. Makers' marks are more often found on 19th- and 20th-century wallpapers, however, either along the front of the paper or on the selvage. If a maker's name is found, refer to books on wallpaper manufacturers such as *A History of English Wallpaper* (Sugden and Edmonson); *The Book of Wallpaper* (Entwistle); *Wallpaper in America* (Lynn); "Wallpaper in Canada 1600s-1930s" (Leung). Again, the experts listed in 2.1 above can be consulted.

2.4 DESIGN REGISTRATION MARK

Wallpaper designers in Britain were able to register their designs after 1839, to protect them from copying. A registered paper was usually stamped with either the registration number or a diamond-shaped registration mark in the selvage. Inquiries about British design registration marks can be made to:

Design Registry
Room 1124A
State House, High Holborn
London WC1 UK

*"First Account Taken" Stamp**Duty Stamp*

Information can be obtained about the manufacturer, date of registration, etc. for a wallpaper with a known registration number. If the registration number is not known (for example, the number or mark is only partly legible) a search can be conducted on the basis of the wallpaper pattern design.

3.0 PAPER ANALYSIS

3.1 IDENTIFICATION OF HANDMADE AND MACHINE-MADE PAPER

Paper is identified as handmade or machine-made both for dating purposes and to understand its characteristics for conservation treatment. All paper was handmade until the 19th-century. The first machine which made continuous rolls of

paper, the Fourdrinier machine, was built in England in 1805 and was in common use there by 1820 (Shorter, pp. 98-106). But tax laws made the use of continuous machine-made paper for wallpaper illegal in Britain until 1830 (Lynn, p. 302). Machine production was also slow to increase until an effective machine for printing continuous rolls of paper was developed. Wallpaper was therefore not produced using machine-made paper on a commercial basis until about 1820 in France and 1835 in the United States (Lynn, pp. 301-2) and until 1841 in England (Greysmith, p. 108) and 1842 in Canada (Leung, p. 311). Some wallpapers continued to be produced with handmade paper as late as the 1870s.

Handmade paper can be distinguished from machine-made by visual inspection. This inspection can be carried out by any careful observer.

3.1.1 Handmade

Handmade paper can be identified by the following characteristics:

a. Horizontal seams:

These occur where the individual sheets of paper are overlapped to form a piece. These seams are best seen under a raking light (see description in Frangiamore, p. 3).

b. An irregular "deckle" edge to the selvage of the paper: (See description in Frangiamore, p. 3 if selvages are present.)

c. Laid lines:

When the paper is held over a strong light source, laid lines appear as pale lines in the paper. They are caused by the slight thinning of the paper where the pulp rested on the wires of the paper mould. They consist of rows of closely spaced parallel lines, crossed at intervals of 5 to 7 cm by thicker lines called "chain lines." Although papermaking machines were adapted to produce fine writing papers with laid lines to imitate handmade papers, these lines would serve no purpose in wallpapers because they would not be visible. Laid lines in a wallpaper therefore indicate a handmade paper.

d. Pronounced wove lines:

Following the use of laid wires in the paper mould, papers were produced on a closely woven mesh like a piece of fabric, which produces wove lines. Without magnification, wove lines appear as a faint mottling. All machine-made wallpapers were made on wove meshes, but wove lines do not necessarily mean that paper was machine-made, since handmade wove papers were produced after the mid-18th century (Shorter, p. 40) and wove paper came into common production after 1800 (Clapp, p. 67). A pronounced wove pattern, produced by relatively coarse screening, indicates either a handmade paper (Lynn, p. 41) or an early machine-made paper (Clapp, p. 71).

e. Watermarks:

In examining handmade wallpaper over a strong light, it may be possible to see a watermark, which is actually a type of laid line. As well as identifying a paper as handmade, the watermark may provide more accurate dating information, since the watermarks used have changed frequently. Also, the date of paper manufacture was often included in the watermark, especially from the 18th century.

A watermark may be partly obscured by opaque paints on the surface of the wallpaper, making it difficult to see even over a strong light source. If particularly important, an

unclear watermark which has been located by transmitted light may be clarified using beta-radiography and similar laboratory techniques (Abbink-Spauk, pp. 95-96).

Once a watermark is found and is clearly visible, it can in many cases be identified by comparison with illustrations in standard reference books. Some of those references are listed in the bibliography.

f. Absence of grain (see 3.1.2 c below):

The fibres in handmade paper are randomly aligned.

When a paper is identified as handmade, the size of the individual paper sheets should be measured and recorded, since sheet size is useful in dating and in determining the country of origin (see Lynn, p. 32). If the paper is a laid paper, the distance between the chain lines and the number of laid lines per centimetre should also be recorded, if possible.

3.1.2 Machine-made

In addition to the absence of handmade characteristics, the characteristics of machine-made papers are:

- a. pronounced wove patterns for early machine-made papers (see 3.1.1 above) or fine wove patterns for later papers;
- b. browned, brittle paper is characteristic of early wood-pulp papers (1850s to 1890s); however, acidity arising from other causes also results in browning and brittleness; and
- c. grain in machine-made papers the fibres are mainly aligned in one direction, that is the direction in which the paper moves as it is formed on the machine. This grain can be seen under magnification.

When a wallpaper is identified as machine-made, the width of the sheet and thickness of the paper should also be recorded (see Lynn, p. 303 and Leung, p. 327).

3.2 FIBRE ANALYSIS

Analysis of the fibres which comprise the paper sheet can be the most important dating test used on a wallpaper sample, especially for 19th-century papers. Fibre analysis is used in dating wallpapers in North America by museums such as the Winterthur and by agencies such as the National Park Service in the United States and Canadian Parks Service (CPS) in Canada. Fibre analysis may also be required by the wallpaper conservator in order to predict and to solve problems which

will arise in the conservation of the paper. Fibre analysis provides information about the raw materials from which the paper is made and the processes used in its manufacture (mechanical, semi-chemical, chemical, sulphite, sulphate, etc.).

From earliest papermaking until 1800, paper was made with linen and – after 1600 – cotton fibres from rags, textile cuttings, ropes and similar raw materials, which were processed by mechanical means. By the 19th century, demand for paper exceeded the supply of raw materials that was available. Pressure for new materials resulted in experimentation and the use of new raw materials and processing techniques. The approximate dates of new introductions are known and are summarized in references such as *Books and Documents* (Grant); *Analysis of Paper* (Browning); *Paper Making in the British Isles* (Shorter) and “Wallpaper in Canada 1600s-1930s” (Leung, p. 355). Fibre analysis can often be used, therefore, to provide fairly precise dating information for 19th- and 20th-century papers.

The fibre content of a wallpaper sample is studied by examining the fibres under a polarizing microscope, in conjunction with a number of simple chemical tests. The tests require a sample of paper about 1 cm². If a piece of the wallpaper cannot be destroyed for testing, it is possible to remove a few single fibres from an edge or tear in the paper with a needle (Grant, p. 45). The sample should be taken from an area which is not badly acid-damaged (that is, brown and brittle) as this damage can make the fibres difficult to identify. If the paper has been through-dyed, it may be necessary to remove the dye chemically before testing, because the colour of the dye may interfere with test results. Few wallpapers are printed on dyed paper however. The paints applied to the surface of wallpapers do not often interfere with testing, as they can generally be either lifted off the surface or dissolved in water.

Under the microscope, the fibres in the sample are examined and their physical characteristics are compared with those of samples of known fibre content. Illustrations of magnified fibres, usually at 100 x magnification, are given in reference books (such as those listed in Clapp, p. 68). Slides of standard fibre mixtures of known proportions are also used for comparison. For the examination methods used, see *Pulp and Paper Microscopy* (Isenberg) and *The Examination of Winterthur Wallpapers* (Clapp).

Chemical tests are used in conjunction with the examination of the physical characteristics of fibres to obtain more accurate information. The prepared slides are tested with various stains

which produce differing colour reactions depending on the fibre composition. Iodine stains, such as the “C” Stain or the Hertzberg Stain, are used for general analysis. The colour reaction of the stain is viewed under the microscope and compared with charts of the colour changes for various fibres (softwood, hardwood, cotton and linen, straws and grasses, hemp, etc.) and manufacturing processes. These charts are given for various stains in *A Colour Atlas for Fiber Identification* (Graff).

Fibre analysis is the job of a fibre expert, since the effects of aging can make the physical characteristics very difficult to identify and the chemical tests require expert interpretation.

3.3 SIZING ANALYSIS

Identification of the sizing materials used in a wallpaper may contribute some dating information, but is more likely to assist the conservator in planning the repair of the paper.

Rosin size can be detected by a number of chemical spot tests, the simplest of which uses a drop of sugar in solution. Internal starch size can usually be detected easily by its reaction to a drop of dilute iodine-potassium iodide solution. Starch surface sizes are more difficult to detect and require more complex testing, because the starches used are usually modified for lower viscosity. For tests which can be used for these sizing materials, see *Analysis of Paper* (Browning, pp. 73-76, 82-85).

Glue size can be detected in a laboratory test which involves boiling a sample of the paper in water (Armitage, p. 105). Glue has been used for paper sizing since about 1350, so the presence of glue size provides little dating information. The absence of glue size, however, indicates that a printing paper was produced after the mid-19th century (Grant, p. 18).

A simple chemical spot test with aluminum can also be applied to sizings to detect the presence of alum (Clapp, p. 25).

When the equipment is available, sizing materials can also be identified using an infrared spectrophotometer.

3.4 pH MEASUREMENT

The acidity of wallpapers is an important indication of their condition and their need for treatment. The extent of browning and brittleness in a paper is a general indication of its acidity, but more precise measurements are often necessary.

A rough indication of paper acidity can be obtained with fairly simple materials and techniques and can be done without the help of a conservator. The pH must be measured at a number of locations within a room, as it may vary considerably. At doorways, for example, acidity may be greater because hands frequently touch the wallpaper or because more airborne pollutants are deposited there by draughts. Wallpaper above radiators and fireplaces, near windows and in various other locations may also be more acidic. As well as measuring the surface of the wallpaper, it is important to measure the acidity of the lining behind the wallpaper and of the back surface of the wallpaper, which will indicate the acidity of the paste. The area of paper to be tested should not be handled with the fingers or brought into close contact with other acidic materials which will affect the pH readings.

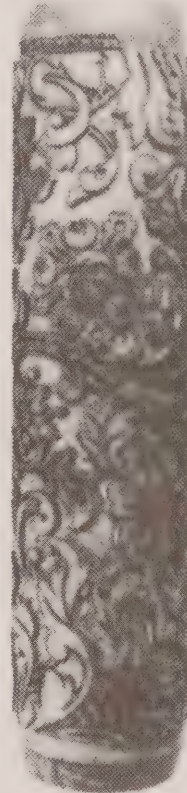
The pH of wallpapers which have been removed from a historic building to a laboratory is usually measured with a pH meter to give a general estimation of acidity. A drop of water is placed on the paper and the pH is determined by pressing a flat-headed glass electrode onto the moistened paper surface. More exact pH measurement in a lab is conducted by simple water extraction methods. In these, a small sample of paper about 1.25 cm square is ground to a pulp with water and the pH of the mixture is measured. This allows acidic materials such as alum to dissolve and to be included in the reading. Extraction methods are often not feasible for historic wallpapers, because each test destroys a piece of the paper, but they can be used for lining papers. For a description of pH meters and extraction methods, see *Analysis of Paper* (Browning, p. 156).

Neither pH meters nor extraction methods are feasible for in situ measurements. Instead, indicator papers impregnated with indicator compounds can be used. Indicator papers are inexpensive and are available in different pH ranges. Those which are sensitive in a short range of about three pH divisions are most useful. Indicator papers are most suited to testing liquids. To give a reading on paper, they must be pressed for two to five minutes on a spot which has been wet with one or two drops of distilled water. Most indicators leave a small coloured stain on the wallpaper because of this prolonged contact. Consequently, they should only be used on selvages, lining papers, back surfaces of papers or inconspicuous locations. One type of indicator, the "Colorphast" strips made in Canada by BDH Chemicals Canada Ltd., is made with dyes that will not bleed into the contacting surfaces. Like other indicator papers, these are made in a wide variety of pH

ranges and can be used to give fairly general indications of pH. These are the same indicator strips which are sold in the U.S.A and Germany under the names "E.M." and "Spezial Indikator." For a full discussion of pH measurement, see *Curatorial Care of Works of Art on Paper* (Clapp, pp. 23-25) and *The Deacidification of Paper and Books* (Smith, p. 109).

For the most important and sensitive wallpapers, even wetting a spot with a drop of water is too destructive a technique. These papers must be left to the conservator.

4.0 PATTERN ANALYSIS



Machine Printing Cylinder with Pattern
Wallpapers in Historic Preservation. *Frangiamore*. 1977.

4.1 APPLICATION OF PATTERN

The way in which the pattern was applied to the wallpaper is identified for both dating and conservation purposes. Patterns were applied by letter press printing (16th to mid-18th centuries), hand painting, stencilling, block printing, machine printing or from the 1930s silkscreen or collotype printing (Greysmith, p. 168). The printing method can be identified by examination with a hand-held magnifying glass of 10x or 20x power. For identifying characteristics, see *Wallpapers in Historic Preservation* (Frangiamore, pp. 3-15).

4.2 PAINT ANALYSIS

Paints are composed of pigments (solid colouring matter) dispersed in a medium (liquid binding material). The pigments may be mixed with large quantities of extenders or fillers, such as chalk or clay bodies. The identification of pigments, fillers and media may be required by the conservator in choosing conservation treatments, or may be used to provide dating information, particularly for late 18th- and early 19th-century wallpapers. White, blue and green paints are of particularly interesting in dating analysis, because they have had very definite, datable changes since the 18th century (Clapp, p. 72). Pigment identification also gives a better idea of the original colour of the paint and the visual effect intended for the wallpaper.

Paint analysis in North America today is carried out mainly with the use of computerized equipment. The CPS Conservation Laboratory currently uses the following equipment: X-ray fluorescence spectrometer, infrared spectro-photometer and X-ray defraction.

4.2.1 X-ray Fluorescence Spectrometer

The CPS spectrometer can use either of two sources of energy:

- a. Radioactive source:
This equipment is used for investigating a large area of paint sample (a circle 1.5-2.5 cm in diameter). The readings given are an average for the area as a whole. The equipment cannot be used for analysing lines or small areas of paint.
- b. Scanning electron microscope (SEM):
This equipment directs a finely focussed beam of electrons at the sample. It is used for very fine work, and can analyse a sample of approximately 1 mm².

The X-ray fluorescence spectrometer can determine those elements present in a sample which have a higher atomic weight than sodium. Since carbon has a lower atomic weight than sodium, this spectrometer does not identify organic components, and cannot be used to analyse paint media. It is useful in identifying the elements present in pigments and fillers, but does not identify the compounds which these elements form.

4.2.2 Infrared Spectro-photometer

This equipment uses an optical system. It identifies both organic and inorganic materials, and can therefore be used to analyse pigments, fillers and media. It identifies compounds, rather than simply elements, and requires a sample of paint approximately 1 cm² (20 to 30 milligrams in weight).

As well as identifying the components of a particular paint, the spectrophotometer can be used to compare paint samples – for instance, to tell whether a badly faded and damaged paint found on one fragment of wallpaper has the same composition as the paint on a well-protected area which has retained its colour.

4.2.3 X-ray Diffraction

This equipment is not computerized. It can provide information which complements that obtained from the X-ray fluorescence spectrometer. It can only be used to analyse crystalline materials, such as most inorganic pigments and fillers. Organic materials are generally not crystalline in structure. An advantage of the X-ray diffraction equipment is that it identifies compounds, rather than simply elements. It requires only a very small sample of paint, approximately 1 mm².

4.2.4 Chemical Methods

Various wet chemistry tests are also used in paint analysis, usually when the equipment described above is not available. Solubility tests can be used in identifying paint media. Gums, glues and gelatines are soluble in water. Casein is insoluble in water, but soluble in ammonia. Oils are soluble in dilute sodium hydroxide. Varnishes are usually soluble in alcohol. The solubilities of paint media and the procedures used for testing them are described by Gettens and Stout and Plesters.

Wet chemistry tests can also be used to identify pigments, but the procedures for chemical testing are far more time consuming and less accurate than the use of spectrometers and

similar equipment. Before chemical tests are undertaken, the pigments which could have been used to produce the paint colour in question are listed. Other dating information which is known about the wallpaper is used to eliminate those pigments which could not have been available. Then chemical spot tests are conducted on small samples of the paint with various acids, alkalis and other reagents and the reactions are studied under the microscope. These procedures and test reactions can also be found in Gettens and Stout and Plesters. Because the microscope is used, micro-tests can be conducted on very small samples of paint.

Natural dyes are often impossible to identify. The lake pigments used extensively in early wallpapers were produced by precipitating natural dyes onto mineral materials, to form a solid pigment. Analysis of lake pigments may therefore only identify the minerals used as precipitants.

4.3 SURFACE COATINGS

Varnishes and the other natural resins on wallpapers are identified by solubility tests, which are also used by a conservator in choosing a solvent with which to remove a varnish coating from a wallpaper. Solubility tests can be conducted either by applying the solvent directly to the wallpaper with a cotton swab and examining the result through a hand-held magnifying glass or microscope, or by chipping off a sample of the coating and applying the solvents to it (Gilmore, p. 84). A solubility chart for some resins is included in *Painting Materials* (Gettens and Stout, p. 52). The solubility of a particular resin varies, however, with its age and handling. Testing is further complicated by the thinness of surface coatings on wallpapers.

Analysis of wallpaper coatings using equipment such as the infrared spectro-photometer also identifies the presence of resinous media. Exact identification of the particular resins present is usually impossible, but also unnecessary. The information which is required is whether a resin vehicle is present and, if so, what its solubilities are for conservation treatment.

5.0 SPOT TESTING

Before conducting conservation treatments on a wallpaper, ensure that the conservator spot-tests any water, solvents or other materials which are considered for use on the paper. The materials must be tested on all the components of the

wallpaper: the paper, the various paints and surface coatings, dirt on the wallpaper, etc. Some methods and examples of spot testing are described in *Curatorial Care of Works of Art on Paper* (Clapp, pp. 56-57), and *Sauvages de la Mer du Pacifique* (Lee et al, pp. 96-97).

6.0 ENVIRONMENTAL FACTORS

If a historic wallpaper is to remain in place without removal, or returned to a building following conservation treatment, it is important to analyse the physical and environmental factors in the building which can contribute to the wallpaper's deterioration. Factors which may need to be monitored are:

- structural movement in the walls
- moisture content of the plaster substrate
- temperature and relative humidity
- levels of illumination, and the proportion of ultra-violet radiation in the light
- air movement (draughts at doorways, etc.)
- air pollution and contaminants

Unless obvious and major problems exist, these factors ideally should be monitored for a year before changes are made to the building, so that seasonal variations are understood. For a description of some methods of measuring the environmental factors, see *Curatorial Care of Works of Art on Paper* (Clapp, pp. 6-14).

7.0 RECORDING

Prior to removal from a wall, wallpapers found in historic buildings must be recorded. This is true both for fragments and large areas of wallpaper. A great deal of the valuable information which wallpapers can provide is lost because they are confused or mislaid. One fragment, which may actually be the earliest wallpaper discovered anywhere, cannot be dated more accurately than to the first half of the 16th century because it was left anonymously at the British Museum with a note that it was removed from "Nacton Hall, Suffolk," and no such building can be traced (Hamilton, p. 201). Documentation of wallpapers prior to their removal is essential for studying the history of the building, for planning and assessing conservation treatments and for returning them to their original positions.

To record its position when a wallpaper is discovered, make measured drawings of the walls or ceilings where it was found, indicating the areas of wallpaper. If available, copies of historic record wall (and ceiling) elevations can be used. Xerographic reductions on high-grade tracing paper or polyester (*Chronaflex*) copies provide an archivally stable format which can be used as base drawings to sketch in quickly and accurately the necessary details concerning each wallpaper of interest. Take photographs, showing both full walls and detailed views and key them to the drawings. Provide written notes about any information which is known about the wallpaper. A special form can be developed for recording such information. Two such forms are included in Appendix 1 as examples. One was developed by architectural conservator Andrea Gilmore for the North Atlantic Historic Preservation Center in the United States. The other is used at the Winterthur Museum.

When conservation or restoration work is to be carried out on a wallpaper, thoroughly document the condition and location of the paper before it is treated or removed from the walls. Take colour as well as black-and-white photographs to record pigment composition and colour before treatment. Photographs should include a code for keying purposes, as well as colour or grey scales so that the colours might be matched to a standard colour classification system. One such documentation was conducted by conservators Patricia and James Hamm:

The wallpaper was photographed with 35mm black-and-white negative film and Ektachrome color transparencies. Each wallpaper panel was divided into three frames. The dado was also divided into separate frames. Each photograph included a number code and color or grey scales. The black-and-white negatives were processed archivally and stored in acid-free folders after being printed on resin-coated paper. The color slides were labeled and presented in clear plastic sleeves in a folder. All photographs were keyed to a diagram detailing their placement. Individual examination report sheets were written on each panel and dado, pointing out tears, losses, stains, etc. A survey report was written on the entire collection of wallpaper, listing dimensions, types of paper, media, binders, etc. (Hamm, p. 119)

Record each sheet or length of wallpaper with sequential numbers or letters as they are taken from a wall, so that they can be reassembled in the same order. Keep all written documentation and records concerning the conservation treatments and materials which are used, to make future treatments easier and more effective. Cross-reference this dossier with the drawings, photographs and other records of the building and contents.

8.0 REMOVAL

Wallpapers must be removed from walls for many conservation treatments which may be required. Because they are damaged so easily by dampness, dirt and structural movement, wallpapers must also be removed during some of the other repair work which is necessary in historic buildings. The decision to remove a wallpaper, rather than to treat it in place, should not be taken lightly. Wallpapers do suffer physical damage during removal, and that damage can be severe. Also, wallpapers lose some of their historic value and integrity with the historic building when they are removed – the original adhesives, seams and wrinkles are lost.

When historic wallpaper must be removed from a large area, an experienced conservator should be involved at least to advise on, and supervise, the removal. Smaller fragments of wallpaper often can be removed quite easily without the involvement of an expert.

Before the removal process begins, the following must be provided:

- a. means of supporting the wallpaper as it is detached from the wall;
- b. means of supporting the wallpaper on a flat surface for transportation to the conservation lab or storage area; and
- c. suitable environmental conditions in the area to which it is being transported that will not result in damage caused by rapid drying, mold outbreaks on damp wallpapers or other reaction.

Also prior to removal, the wallpaper must be inspected to ensure that it can be removed without causing major damage to fragile paint and paper layers. Weakly bonded and cracked areas of the paint surface, and badly weakened and torn areas of the paper, may need to be consolidated by a conservator before they can be safely handled (see Section 8.4 “Wallpaper: Consolidation and Repair”).

When wallpapers are pasted to plaster walls, with or without a lining paper, it may be possible to remove them by simply inserting a palette knife or flat blade under the paper and gently sliding it back and forth to release the paper. This is often possible when old wallpaper paste has dried out and lost its adhesive qualities or when the wall and paper have become wet and the paste has been dissolved. If the adhesive

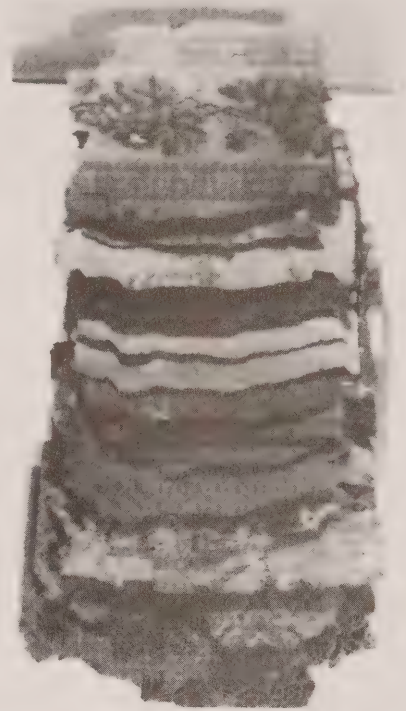
does not come away easily, it may be possible to cut the wallpaper away from the wall by cutting through the lining paper behind and removing the lining from the wallpaper with more precise techniques in a conservation workroom. It is necessary to support the wallpaper as it is being removed and to prepare a flat, well-supported carrier to receive the wallpaper as it comes off the wall. If the paper has wet paste on its reverse side, the carrier may need to be covered with a material to which the paste will not stick, such as waxed paper (if only a little paste is present) or polyester film.

Another way of removing wallpapers or of separating several layers is by applying steam to the paste behind the wallpaper. This technique is described by Frangiamore:

Applying a little moisture will usually soften old wallpaper paste sufficiently to get stubborn samples off the wall in a reasonable state of preservation. A good method is to use a small, hand-held steamer, such as those sold for home-and-travel steaming of clothes. Choose a steamer with a head that produces a line or a point of steam that can be concentrated on a limited area.... Start from the bottom of the sample and work up.

Try to wet the paste, not the paper (although the paper is obviously going to absorb some of the moisture). Start steaming in a corner or another point where the paper is already loose and the jet of steam can be directed under the paper right at the paste. Sometimes this is not possible, and you have to start by pointing the steamer straight at the paper. As soon as possible, peel the paper away from the wall and direct the steam at the paste. While steaming, use a piece of screening to "catch" and support the paper removed from the wall. (Wire window screening with the edges protectively covered with masking tape works best, although a blotter will also suffice.) The operation is easier with two people: one to steam and one to support the paper as it comes off.

It is hard to predict how many multi-layers of paper will come off the wall. The easiest method is to remove the whole "sandwich" of layered papers. Then you can steam them apart afterwards, separating them and laying them flat on a table. If you have no need for the intervening layers, do be sure to identify them and send them to a museum specializing in wallpaper collections (Frangiamore, pp. 2-3).



Thirteen Layers of Wallpaper
Papers have been steamed apart and arranged to show the patterns in sequence. Wallpapers in Historic Preservation. Frangiamore. 1977.
Courtesy USDI.

It is important that the steam used does not "spit" droplets of water, as these can stain the paper and dissolve paints. The steaming may result in some colour loss with water-soluble pigments, but not as much as occurs when layers of paper are soaked apart in a water bath. Papers with fragile paint-areas may begin to lose flakes of paint from the surface as the steam moistens the paper from the back and the paper expands (Lee et al, pp. 96-97). Watch for damage while papers are being steamed and stop the steaming process if paints run or flake.

Some papers may prove impossible to remove from their backings without destroying them, particularly those pasted directly onto wood panelling. In this case, a decision must be made on the relative importance of the wallpaper and its backing. The wallpaper may be removed from the building with its supporting surface and stored in a controlled environ-

ment to prevent further deterioration of the paper, if it is of sufficient importance. If a historically important wallpaper is very small in area, precise techniques can be used to remove it from a difficult backing. Hand-painted Indian Mogul miniatures which had been applied to the walls of a baroque palace in Austria were recently restored and were found to have been glued directly to wooden boards. They were removed from the wood using steam directed from a small metal-reinforced tube and then residues of glue were removed with a scalpel (Jahoda and Rosenberger). However, these techniques are too time-consuming and costly to use on wallpapers which cover much larger areas. It may be necessary to use less careful methods and to accept some colour loss, when large areas of less important papers are being removed and will not loosen with steam.

Soaking wallpaper in a water bath is one such method. Soaking with water should not be undertaken by non-conservationists, unless the wallpaper is of no value and can be destroyed. The papers can be soaked apart in situ with water-saturated blotters held against the surface or the layers of wallpapers and linings can be soaked apart by immersion in a water bath. Room temperature or lukewarm water is usually used, but cool water may be needed to avoid dissolving the paints when glue or gelatine is the binding medium. When not in place, the papers are supported and soaked in a large flat bath or saturated with a gentle flow of water, as described in 8.4 "Wallpaper: Consolidation and Repair." They must not be allowed to soak too long or the paper will become pulpy and disintegrate. As soon as the layers can be separated, a support such as wire screening is slid under the top layer and it is carried on this tray to a drying surface. If most of the paste has been washed away, it can be spread out on blotter paper, waxed paper or tin foil (Frangiamore, p. 3). Wallpaper must be dried slowly and weighted during drying to ensure flatness.

When wallpapers were hung with glues or pastes which were not water-soluble and which will not respond to the heat from steaming, it may be necessary to remove them with solvents. Various solvents are tested on the paste with cotton swabs until one is found which will dissolve the glue without damaging the wallpaper. The solvent is then applied to the glue with cotton swabs or cloth. If solvents do not work, it may be possible to use enzymes to break down the glues. The use of enzymes is still experimental (see Shelley).

Wallpapers which are hung on a scrim of canvas, linen or hessian are removed from the scrim and intermediate lining

papers using the various techniques described above. The scrim often must be removed from the walls first, however, and this in itself is problematic since large areas are involved and the material must be supported carefully at all times. The same problems are encountered when any large areas of wallpaper must be removed, with or without lining scrims. The following are three accounts of ways in which wallpaper was supported during removal:

1. The first phase of conservation was to remove the paper from the walls and devise a safe system for transporting the large unwieldy panels to storage and work areas. Because of the danger of flaking paint, the entire procedure was governed by the necessity to avoid bending the wallpaper during removal. The initial step in this operation was to expose the horizontal edges of the panels by removing all molding and woodwork. Where vertical boundaries were not defined by the architecture, seams had to be cut to make the panels more manageable in width (5', 6' and 7-1/2') for handling and treatment. In some instances irregular cuts skirting the scrollwork were made; elsewhere, as in the very large scenic panel, *The Roman Ruins*, seams were cut directly through the design.

The weak bond between the canvas backing of the paper and the masonite walls facilitated detachment of the panels. To release the edges small clay-modelling spatulas were used; the more inaccessible central areas were reached with a very long handled spatula made of acrylic, about 2" by 18", with a beveled end. The problem to contend with at this stage was to prevent the separated panels from falling to the ground under their own weight. The following system was thus devised. Prior to separating the panels entirely from the walls, only the top twelve inches were released using the tools described above. The exposed canvas was mechanically pulled away from the lined wallpaper and the fabric was then stapled to a wooden strip into which eye hooks had been screwed. These hooks, placed along the top edge of the strip, in turn were attached to nails in the wall. Secured from the top by this supporting rail, the panels thus could be gradually detached from the masonite, allowing them to remain in place yet hang free until time came to remove them from the room. The wooden supports also served as a means

of attaching the panels to side trucks so that they could be transported without bending, and to hang the panels in storage (Shelley, p. 131).

2. Phillip Stevens [paper and paintings conservator in London, England] has developed a method of support which he used in removing an 18th-century Chinese wallpaper mounted on canvas. He cleaned and removed the paper border which was pasted over the vertical joints between panels of wallpaper, and found that the canvas scrim was folded under at the edges and tacked to wood strapping with hidden tacks. He provided a horizontal 1" x 2" timber support at the top of the wallpaper, supported on rope from hooks in the picture rail. The timber was covered in paper to protect the wallpaper. He removed the top 4" of a panel of wallpaper, tearing the hidden tacks through the canvas scrim. He fastened this top section to the timber 1 x 2 with bulldog clips, and then was able to work down the panel, gradually releasing the tacks until the wallpaper was hanging loose, fully supported by the timber 1 x 2. One person then lowered the 1 x 2 with the ropes by which it was hanging, while another person held the bottom end of the wallpaper, walking away to keep it straight. The paper was then lifted onto a carrier for transportation (Myers, p. 87).
3. When restoration [of Clandon Park, Surrey] began in 1968, the hessian scrim on which the paper was hung had bulged and sagged badly, the iron nails tacking the scrim to wood battens had rusted, and the wallpaper needed cleaning. Mr. James Smart removed the paper from the walls by first applying a large frame over it. With the frame holding the paper firmly against the battens behind, he cut the scrim at the edges and tacked it to the frame, then lowered the frame off the wall, along with the wallpaper (Myers, p. 115).

cannot be returned to its room for a period of time and, if available funds are low, this period may be several years. In these cases, the wallpaper must be stored in light- and dust-free conditions where the temperature and relative humidity are controlled.

One way of storing small fragments is to treat them like prints and mount them on stiff acid-free mat boards, with covering boards which have openings cut in them to show the wallpaper. This technique is described in *Rescuing Historic Wallpaper* (Frangiamore, pp. 3-4), and in *Curatorial Care of Works of Art on Paper* (Clapp, pp. 71-76, 124). The wallpaper should be mounted on the mat board with hinges of acid-free paper, so that its reverse side can still be studied. This is often the best way of storing small delicate fragments, since it supports them on a rigid surface.

Another useful way of storing wallpaper fragments after cleaning and conservation treatment is to encapsulate them between two layers of acid-free polyester film. The technique is described and illustrated in *Wallpapers in Historic Preservation* (Frangiamore, pp. 46-48). Its advantages are that encapsulated papers can be safely handled for study, the reverse side of the paper is fully visible and, because the sample is held in place by static electricity, tears can be tacked just at the edge rather than fully mended. Disadvantages are that, if the two sheets of polyester are sealed with double-faced tape, the adhesive can cause damage if the wallpaper slips and comes into contact with it, and the adhesive in the tape can melt and creep into the paper under adverse storage conditions. Preferable methods of encapsulation are those of sewing the two sheets of polyester together (Greenfield, p. 29) and of welding the edges of the polyester together ultrasonically. Encapsulation may not be suitable for large numbers of wallpaper samples, because the polyester film is heavy and storage may create a weight problem. Encapsulated samples should be stored in light-free drawers or shelves.

If large areas of wallpaper must be stored, every effort should be made to avoid rolling the paper; if it is to be stored for long periods, it should be laid flat on blotters or acid-free paper on a well-supported surface. Some wallpapers can be rolled for short periods of time without causing damage such as flaking of pigments. They must always be rolled on a supporting core, of about 60 cm in diameter, with the pattern side facing out and must be inter-leaved with acid-free paper. They should be fumigated before storage, since they cannot be unrolled frequently for inspection for moulds and insects.

9.0 STORAGE

When wallpapers have been removed and treated, they will not necessarily be re-hung. The paper may be only a small fragment, or a room of paper may not contain enough areas in good condition to justify rehanging in the same room. Construction work in the building may mean that a wallpaper

10.0 APPENDIX: FORMS

**NORTH ATLANTIC PRESERVATION CENTER
WALLPAPER SAMPLE IDENTIFICATION FORM**

Site and Sample Identification No. _____

I. Source of Wallpaper Sample

- A. Park _____
- B. Structure _____
- C. Room _____
- D. Substrate
Plaster _____ Wood _____ Other _____
- E. No. of Layers of Wallpaper in Sample _____
- F. No. of the Layer of Wallpaper Being Documented _____

II. Wallpaper Sample Identification

- A. Pattern _____
- B. Manufacturer _____
- C. Date of Manufacture _____
- D. Method Used to Date Wallpaper _____

III. Physical Characteristics of Wallpaper Sample

- A. Size of Sample _____
- B. Portion of Wallpaper Sampled _____
- C. Principal Colors _____
- D. Texture of Paper
Smooth _____ Rough _____ Waffled _____
- E. Method of Paper Manufacture
Handmade _____ Machine-made _____
- F. Technique for Producing the Printed Design
Hand Painted _____ Stencilled _____
Block Printed _____ Machine Printed _____
- G. Evidence of Surface Coating
Varnish _____ Shellac _____ Paint _____
- H. Type of Paper
Rag _____ Chemical Wood _____
Mechanical Wood _____ Combination _____
- I. Type of Paint
Water Soluble/Chalky – Distemper _____
Non-Water Soluble – Oil _____

IV. Photographs

- B & W Slides _____ Color Slides _____
- B & W Prints _____ Color Prints _____

Form prepared January, 1980 by Andrea M. Gilmore, Architectural Conservator

SAMPLE FORM NO. 1:

Wallpaper Identification Form Used by the North Atlantic Historic Preservation Center, National Parks Service, Boston, MA.

(From Gilmore, 1981, p. 82).

HANDMADE ☐LAID ☐WOVE ☐MACHINE-MADE ☐**WALLPAPER EXAMINATION**

PROVENANCE OF SAMPLE:

DESCRIPTION OF SAMPLE INCLUDING DATE AND COUNTRY OF ORIGIN (actual or estimated):

PAPER:

IF HANDMADE, SIZE OF SHEET _____

IF LAID, INTERVALS BETWEEN CHAINS _____ ; NUMBER OF LAIDS PER CENTIMETER _____

IF MACHINE LAID, WIDTH OF SHEET, DESCRIPTION OF REVERSE:

FIBER CONTENT:

PAINT:

SOLUBILITIES:

CHEMICAL COMPOSITION:

HAND PAINTING ☐STENCIL ☐BLOCK PAINTING ☐PRINTING WHEEL ☐MODERN ☐**DETAILED DESCRIPTIONS:**

PATTERN:

PAPER CONDITION AND MOUNTING:

DISTINGUISHING MARKS:

LOCATION OF MARKS:

SAMPLE FORM NO. 2: PART A
Wallpaper Examination Form Used by the Winterthur Museum.
(From Clapp, 1981, p. 69).

CEILING BORDER

PAPER:

PAINT:

PATTERN:

MARKS:

CHAIR-RAIL BORDER

PAPER:

PAINT:

PATTERN:

MARKS:

DADO

PAPER:

PAINT:

PATTERN:

MARKS:

SAMPLE FORM NO. 2: PART B
Wallpaper Examination Form Used by the Winterthur Museum.
(From Clapp, 1981, p. 70).

11.0 BIBLIOGRAPHY

- Abbink-Spauk, S.A.** 1976. "The Technological History, Dating and Analysis of Wallpaper," Unpublished dissertation at the Institute of Archaeology, London.
- Armitage, F.D.** 1957. *The Atlas of Paper-making Fibres*. Guildhall, Epsom, UK.
- Association for Preservation Technology, The.** 1977. "Paint Color Research and Restoration of Historic Paint," Publication supplement. Ottawa.
- Briquet, C.M.** 1968. *The New Briquet*. Amsterdam.
- Browning, B.L.** 1969. *Analysis of Paper*. Dekker, New York.
- Churchill, W.A.** 1935. *Watermarks in Paper in Holland, France, England, Etc., in the XVII and XVIII Centuries and Their Interconnection*. Illustrated. Reprinted 1967. Hertzberger, Amsterdam.
- Clapp, A.F.** 1978. *Curatorial Care of Works of Art on Paper*. 3rd revised ed. Intermuseum Conservation Association, Oberlin, OH.
- _____. 1981. "The Examination of Winterthur Wallpapers and a Progress Report, April 1980, on a Group of Papers from the Fisher House, Philadelphia," *Journal of the American Institute for Conservation*, Vol. 20, No. 2 (Spring), pp. 66-73. Washington, DC.
- Crown, D.A., and M. Crim.** 1968. *The Forensic Examination of Paints and Pigments*. Charles C. Thomas, Springfield, IL.
- Entwistle, E.A.** 1954. *The Book of Wallpaper: A History and an Appreciation*. Reprinted 1970. Kingsmead Reprints, Bath, UK.
- _____. 1964. *Wallpapers of the Victorian Era*. F. Lewis, and Metuchen, NJ Textile Book Service, Leigh-on-Sea, UK.
- Flood, P.** 1959. "Dating Morris Patterns," *Architectural Review*, Vol. 126 (July), pp. 14-20.
- Frangiamore, Catherine L.** 1974. *Rescuing Historic Wallpaper: Identification, Preservation, Restoration*. Technical Leaflet 76. American Association for State and Local History, Nashville (See also, Lynn, C.). Quoted material reprinted by permission: American Association for State and Local History, 172 Second Avenue North, Suite 202, Nashville, TN., 37201
- _____. 1977. *Wallpapers in Historic Preservation*. National Park Service. U.S. Department of the Interior, Washington, DC.
- Gettens, R.J., and G. L. Stout.** 1936. "The Stage Microscope in Routine Examinations of Paintings," *Technical Studies in Conservation*, Vol. 4 (April).
- _____. 1942. *Painting Materials*. Dover, New York.
- Gilmore, A.M.** 1979. "Wallpaper Conservation for the Architectural Conservator." Unpublished dissertation. Graduate School of Architecture and Planning. Columbia University, New York.
- Graff, J.H.** 1940. *A Color Atlas for Fiber Identification*. The Institute of Paper Chemistry, Appleton, WI.
- Grant, J.** 1937. *Books and Documents, Dating, Permanence and Preservation*. Grafton, London.
- Gravell, T.L., and G. Miller.** 1979. *Catalogue of American Watermarks: 1690-1835*. Garland Publishing, New York.
- _____. 1983. *A Catalogue of Foreign Watermarks Found on Paper Used in America, 1700-1835*. Garland Publishing, New York.
- Greenfield, J.** 1981. *Paper Treatment*. Yale University Library, New Haven, CT.
- Greysmith, B.** 1976. *Wallpaper*. Studio Vista: Cassell & Collier MacMillan, London.
- Hamilton, J.** 1977. "Early English Wallpapers," *Connoisseur*, Vol. 195, No. 785 (July), pp. 201-6.

- Hamm, Patricia, and James Hamm.** 1981. "The Removal and Conservation Treatment of a Scenic Wallpaper, Paysage à Chasses, from the Martin Van Buren National Historic Site," *Journal of the American Institute for Conservation*, Vol. 20, No. 2 (Spring), pp. 116-25. Washington, DC. Quoted material reprinted with permission: American Institute for Conservation of Historic and Artistic Works, 1400 Sixteenth St., NW, Washington, DC. 20036 (202)232-6636. Copyright 1981.
- Isenberg, I.H.** 1967. *Pulp and Paper Microscopy*. The Institute of Paper Chemistry, Appleton, WI.
- Jahoda, K., and H. Rosenberger.** 1980. *Wall Decorations on Paper in Baroque Castles in Austria, Part 1: The Chamber of Millions in the Palace of Schönbrunn*. Conservation within Historic Buildings. Vienna Congress, IIC, London, p. 176.
- Leask, A.L.** 1965. "Excise Marks on English and Irish Wallpapers," *Antiquities*, Vol. 88, No. 2 (August), pp. 216-19.
- _____. 1966. "Some Later Excise Marks on English Wallpapers," *The Paper Maker*, Vol. 35, No. 2. Hercules Powder Co., Inc., Wilmington, DE.
- Lee, M., W. K. Bachman and Shelley Fletcher.** 1978. *Sauvages de la Mer du Pacifique: Treatment of an Early 19th-century Wallpaper Depicting the Voyages and Death of Captain Cook*. Preprints of Papers Presented at the 5th Annual Meeting of the American Institute for Conservation of Historic and Artistic Works, Boston, 30 May – 2 June 1977. AIC Preprints. American Institute for Conservation, Washington, DC.
- Leung, Felicity L.** 1983. "Wallpaper in Canada 1600s-1930s," Microfiche Report Series 208, Vols. 1 and 2 (illustrations). Parks Canada, Ottawa.
- Longfield, A.K. (Leask).** 1962. "Old Wall-papers 6. Legislation and Marks," *Journal of the Royal Society of Antiquaries of Ireland*, No. 42, pp. 91-116.
- Lynn, C.** 1980. *Wallpaper in America, From the Seventeenth-century to World War I*. W.W. Norton & Company, Inc., New York (see also Frangiamore, C.L.).
- Myers, S.** 1981. "The Conservation of Wallpapers in Historic Buildings." Unpublished dissertation. Institute of Advanced Architectural Studies. University of York, York, UK.
- Oman, C.C., and J. Hamilton.** 1982. *Wallpapers: An International History and Illustrated Survey from the Victoria and Albert Museum*. Harry N. Abrams, Inc., New York. Illustrations reprinted by permission: Courtesy of the Board of Trustees, Victoria and Albert Museum, London.
- Plesters, J.** 1955-56. "Cross-sections and Chemical Analysis of Paint Samples," *Studies in Conservation*, Vol 2, pp. 110-57.
- Shelley, M.** 1981. "The Conservation of the Van Rensselaer Wallpaper," *Journal of the American Institute for Conservation*, Vol. 20, No. 2 (Spring), pp. 126-38. Washington, DC. Quoted material reprinted with permission: American Institute for Conservation of Historic and Artistic Works, 1400 Sixteenth St., NW, Washington, DC. 20036. Copyright 1981.
- Shorter, A.H.** 1957. *Paper Mills and Paper Makers in England 1495-1800*. Hilversum. Special reference to late 17th century and 18th century.
- _____. 1959. "Watermarks in English Paper," *The Paper Maker and British Trade Journal*, No. 137. Special reference to early 19th century.
- _____. 1971. *Paper Making in the British Isles*. David and Charles, Newton Abbot.
- Smith, R.D.** 1975. "The Deacidification of Paper and Books," *American Libraries* (February), pp. 108-10.
- Sugden, A.V., and J.L. Edmonson.** 1925. *A History of English Wallpaper 1509-1914*. B.T. Batsford, London.

Illustrations are the property of the Heritage Conservation Program, unless otherwise noted.

VOLUME VI

CONSERVATION OF MATERIALS

8.4

WALLPAPER

CONSOLIDATION AND REPAIR

PRODUCED BY:
HERITAGE CONSERVATION PROGRAM
ARCHITECTURAL AND ENGINEERING SERVICES
PUBLIC WORKS CANADA FOR ENVIRONMENT CANADA
OTTAWA (819) 997-9022

ORIGINAL DRAFT: S. MYERS

CONTENTS

1.0 INTRODUCTION

2.0 APPROACHES TO TREATMENT

- 2.1 CONSERVATION IN PLACE
- 2.2 REMOVAL AND REHANGING
- 2.3 REPLACEMENT WITH A REPRODUCTION

3.0 CONSOLIDATION

- 3.1 PLASTER SUPPORT
- 3.2 PAINT
- 3.3 PAPER

4.0 CLEANING

- 4.1 DRY CLEANING
- 4.2 SOLVENT CLEANING
- 4.3 WASHING WITH WATER

5.0 DE-ACIDIFICATION

6.0 TEARS AND HOLES

7.0 CREASES

8.0 PAINTS

- 8.1 IN-PAINTING

9.0 SURFACE COATINGS

10.0 MOULDS

11.0 INSECTS

12.0 BIBLIOGRAPHY

2.1 CONSERVATION IN PLACE

Conservation of the wallpaper without removing it from the wall has several advantages. It maintains the greatest portion of the original fabric, including original pastes, joints and wrinkles. In-place conservation can also be carried out in less time and at a lower cost than other alternatives.

Its main disadvantage is that only a limited range of treatments can be applied to an unremoved wallpaper. There is a risk that defects, such as acidity, will be corrected only partially, so that degradation of the wallpaper will continue. Large wrinkles must remain in the paper and tears may be impossible to repair. Therefore, wallpapers can be treated in situ only if they are no more than moderately degraded. Also, the walls and building as a whole must be stable, fairly sound and dry.

If wallpapers are to remain in place while other repairs are carried out on the building, they must be thoroughly protected from damage by water, dirt, abrasion and so on. If the repairs make humid conditions likely, historic wallpapers may need to be removed to prevent damage from outbreaks of mould growth.

2.2 REMOVAL AND REHANGING

The advantages of this approach are: all surfaces of the wallpaper can be examined and treated; adhesives, moulds and linings which are contributing to degradation can be removed; and the walls and structure of the building can be thoroughly examined and repaired. Wrinkles can be removed from the wallpaper if necessary, tears and holes can be properly mended, the paint surface can be consolidated and flattened more easily and treatments such as cleaning and de-acidification can be applied more evenly and thoroughly. Also, the wallpaper can be remounted in a way that will prolong its life and make removal easier in the future.

Disadvantages are that some wallpapers are not strong or flexible enough to withstand removal. Any removal involves the risk of damage to the paint and paper layers of any wallpaper. Removal also destroys some of the integrity of the wallpaper within the context of the historic building in which it is hanging. Techniques for removal of whole rooms of wallpaper cannot be as precise and delicate as those used in the conservation of prints and drawings, because of the expense and time involved. Rehanging techniques, such as use of new scrims or independent frames, require consideration

of the effect they will have on other parts of the building, such as decorative wood trim and mouldings. Finally removal and rehanging involve more time and expense than conservation work on wallpaper in situ. For a case study which explains why removal was considered essential for a particular wallpaper, see the article "The Removal and Conservation Treatment of a Scenic Wallpaper" (Hamm and Hamm).

2.3 REPLACEMENT WITH A REPRODUCTION

A reproduction wallpaper may be considered as a solution when very little original wallpaper remains. However, this approach can involve many problems. Reproductions of hand-made wallpapers on continuous machine-made paper do not have the uneven surfaces and visual liveliness of the handmade originals composed of small sheets of paper pasted together. Compromises are often made in the colours, materials and even the scale of a wallpaper reproduction because of cost and the final product may be so compromised that an unpapered wall would have been preferable. Reproduction wallpapers also tend to receive far less maintenance, inspection, protection from abrasion and other care than do original materials, so that they may quickly look battered and damaged or they may be replaced frequently and increasingly carelessly.

This approach is the one which requires the greatest consideration and involvement from the owner and the designers of a conservation project. Replacement of wallpapers with reproductions involves many conservation decisions. The reproduction can be made to resemble the aged appearance of the wallpaper or to imitate the appearance it is believed to have had when new or only slightly aged. When fragments of several wallpapers are found in a room, a choice must be made of which to reproduce. A decision must be made whether to reproduce the wallpaper found in a room or to replace it with a commercially available reproduction of a pattern of the same period, sacrificing accuracy of appearance but possibly saving a great deal of expense.

For information on reproduction wallpapers, see Frangiamore, and Richards.

3.0 CONSOLIDATION

Consolidation treatments include those which are used to strengthen the various layers of wallpaper and to turn separating or fractured parts into a whole.

3.1 PLASTER SUPPORT

Consolidating loose, crumbling plaster behind a wallpaper may become the job of professional conservators during an *in situ* wallpaper conservation, because of the care which must be taken to avoid damaging the wallpaper. Plaster can be consolidated in some cases without removing wallpaper, by injecting consolidants such as various organic polymers. Sometimes plaster can be re-attached to laths or other supports, with wallpaper in place, by injecting adhesives. For a fuller discussion, see Phillips, pp. 87-89 (1981). For examples of plaster consolidation with wallpaper in place, see Hamburg, p. 93; Schulte, p. 101 and McClintock, p. 114.

3.2 PAINT

Areas of flaking, cupping or brittle paints may need to be treated with a consolidant to re-adhere them to the paper before any other treatments can be undertaken. A consolidant solution also may be applied to the entire surface of the paper. This is preferably not done until other treatments are completed because the consolidant tends to hold wrinkles and can make other repairs more difficult.

Flaking paints may be re-adhered with the wallpaper *in situ*, but there is a risk of only partially solving the problem by treating just the front surface of the wallpaper. Paints are often re-adhered by carefully brushing or flowing a synthetic adhesive over the flaking area – the adhesive is gently forced behind the paint flakes. As they become moistened and relaxed, the loose flakes are gently pressed back against the paper. This must be done patiently and meticulously. The choice of adhesive for a particular area of flaking paint varies with the composition, colour, thickness and surface area of the paint, as well as the materials and condition of the paper. The choice must be made by a conservator familiar with the adhesives and their properties. Testing is done on small areas until a material with good adhesion and little visual effect (colour, texture, mattness) is found. Some of the adhesives used are solutions of methyl cellulose in water (for papers which can withstand aqueous techniques), polyvinyl acetates of varying viscosities, soluble nylon and glue and gelatine sizes. When further treatment of the paints is required the adhesive may be applied to the back of the wallpaper and allowed to soak through to the paint layer (Fiedler, p. 179).

Do not paint over flaking paints with a varnish or spray with a fixative to re-adhere them. Neither material provides proper adhesion and both produce shiny finishes. They are also de-

structive of the wallpaper in the long term. Facings of thin paper such as lens tissue or thin Japan paper are sometimes applied to areas of a wallpaper to protect and consolidate paints prior to other treatments.

Examples of paint consolidation are described in: Hamburg, p. 96; Schulte, p. 105; Hamm and Hamm, pp. 120-21; Shelley, pp. 131-33; Lee, Bachmann and Fletcher, pp. 96-98; Fiedler, p. 179.

3.3 PAPER

Weak, fractured paper often requires consolidation, and this may need to take place before other treatments – such as removal of acidic linings and adhesives – can begin. Paper which is delaminating in layers may be consolidated by injecting adhesives. Weak paper may be faced with fine tissues or lined with a lightweight consolidating lining. For descriptions of examples, see 3.2 above.

4.0 CLEANING

Cleaning old wallpapers is the conservation treatment most likely to be used, especially in buildings where funds are not available for extensive conservation. Dust, cobwebs, soil and minor grease marks can often be removed with simple dry-cleaning techniques. These can be done with the wallpaper in place and while time-consuming, involve fairly ordinary materials, rather than highly specialized techniques. Because of this, they are often undertaken by people who are not trained conservators. Important historic wallpapers should never be cleaned without the involvement of a professional conservator.

A traditional method of cleaning wallpapers which is still used occasionally in Britain is the “stale bread” technique. This was used to clean wallpapers at the Brighton Pavilion in the 1950s, and the wallpaper in the Green Drawing Room at Clandon Park, Surrey, in 1968. The process is described in a 1903 publication:

Perhaps the best method of cleaning papers is by the old ‘stale bread’ process. Some do this by crumbling the bread and rubbing the crumbs on the paper, holding a paper in one hand to catch the crumbs as they fall; but a better plan is to rub with a load (sic) of bread. Choose a stale loaf that is not hard, cut off the end square and remove the crust, say half an

inch, on each side. Then rub the paper with it, and as soon as it is soiled cut off a very thin slice and go on rubbing. If a very thin knife is used and care is taken to remove only a very thin slice each time, the loaf will last a long time (Jennings, p. 113).

The same book gives other cleaning suggestions. One alternative described is rubbing the wallpaper with a handful of bran on a large flat sponge. Another is a technique for removing smoke darkening, by putting a piece of soft cotton flannel (nap side out) over a soft broom and wiping down the wall with it with regular strokes. The suggested technique for flock papers and others having a soft nap is dusting with a soft bristled brush or a fine feather duster. Traditional cleaning techniques like these have tremendous appeal and seem right because they are the techniques which would have been used at the time the historic building was decorated and lived in. Traditional cleaning methods, because they are well tested, often can be used safely on modern wallpapers.

For a historic wallpaper, however, traditional methods are generally too abrasive to be used. Even when the paints and paper seem to be unaffected by the abrasive action, some of the surface is being worn away. The less abrasive the cleaning techniques, the longer the wallpaper will last. Also, rubbing with a loaf of bread, bran-covered sponge or flannel-covered broom are not very controlled techniques and damage can be done to more delicate areas before the fault is noticed. Because wallpapers cover such large areas, the delicate and time-consuming techniques used to clean prints and drawings are often not feasible for them. If funds are not available for careful and time-consuming cleaning methods, it may be preferable to clean only one panel or one wall of paper carefully, rather than using abrasive and destructive methods on the entire room.

Other more modern techniques may also be too abrasive or unsuitable for a particular wallpaper. They must be tested on small areas before general use and their effects noted and compared. Old stains and embedded dirt may be resistant to cleaning and their presence may have to be accepted, especially on papers which are in a delicate condition. If the paper is soft or has a felt-like surface, it will be scuffed and polished by any but the gentlest techniques. The gentler techniques should be tried first and more abrasive methods and greater pressure used only if the dirt does not respond.

4.1 DRY CLEANING

The dry cleaning techniques discussed here do not involve the use of any form of liquid. They are listed in order of increasing abrasiveness, or force:

- a. removal of clinging dirt and cobwebs with tweezers or a dry sable or ox-hair artist's brush;
- b. removal of loosely attached dirt by dusting gently with such a brush;
- c. blowing off loose dust and dirt with careful use of low pressure air jets from a spray gun, if the paints are stable and firmly attached to the paper (Clapp, p. 59);
- d. vacuuming off loose dust and dirt with a fine nylon fabric screen held between the wallpaper and the vacuum nozzle, if the paints are stable and firmly attached;
- e. rubbing with crumbled or finely powdered gum rubber, or crumbled eraser such as Opaline cleaner or draft-clean powder (on horizontal surfaces) with the paper off the wall;
- f. rubbing with an Opaline pad (on vertical or horizontal surfaces);
- g. removal of persistent marks with soft solid erasers such as art gum, Pink Pearl, or vinyl erasers;
- h. use of air-abrasive pencils to deliver a small jet of fine abrasive powder;
- i. use of electric erasers (with a soft eraser) to break up stubborn marks (of limited use because they polish paper, make it shiny and can be too abrasive).

Fuller descriptions of many of these techniques are given in Clapp, pp. 59-60.

Dry atmosphere is required for dry cleaning of wallpapers, to prevent damage to the paper and paints and to prevent the dirt from being smudged on the wallpaper. If dry cleaning is done with the paper in place, the room may need to be slowly dehumidified beforehand. Permanently reducing the humidity may be required.

4.2 SOLVENT CLEANING

The term dry cleaning is also used occasionally to include cleaning with solvents which are non-aqueous. Solvents are used to clean greasy dirt from wallpapers. Their choice and use is the job of the paper and paint conservator. Both the paint and



Fading Colours in 18th-Century Wallpaper

paper of a wallpaper can be damaged easily by solvents, that may affect the sizing or the colour of the paper, or may dissolve the paints. Spot tests are therefore conducted on all the materials of the wallpaper before a solvent is selected. Solvents which seem safe may dissolve certain pigments such as Prussian Blue. The binders in old pigments may have disintegrated to the point that they will be destroyed by solvents which should be safe with those pigments.

In general, the weakest possible solvents are used. They are tested in order of increasing solvent strength. The selected solvent is applied with a soft brush or large cotton swab, with gentle pressure and repeated strokes. When possible, immersion in a shallow pool of solvent for ten minutes or so may be useful. After the greasy medium of the dirt has been broken down by a solvent, a second use of crumbled eraser may remove the loosened dirt (Clapp, p. 60).

Bleaching wallpapers to remove stains such as foxing marks should be avoided. The bleaching compound leaves chlorine deposits behind that can damage the paper by oxidizing the cellulose fibre molecules as well as the stain (Plenderleith and Werner, p. 81). It is better to leave stains than to shorten the life of historically-important paper with bleaching treatments.

4.3 WASHING WITH WATER

Some wallpapers can be immersed and soaked in water. This may be undertaken in order to loosen pastes which adhere paper to linings, to remove adhesives and other materials which have soaked into and discoloured the paper, to loosen surface dirt and to reduce acidity. Some old papers seem to be improved by bathing in water, perhaps because the fibres and sizing swell and re-establish a more firmly intermeshed structure. Washing wallpapers must be left to the conservator. Washing is a major treatment. Handling wet papers without damaging them requires skill and specialized techniques.

Many historic wallpapers cannot be treated with water – for instance, those with water-soluble paints and those which are very fragile, brittle and broken. The paper and paints must be tested for reaction to water before washing is undertaken. Papers with bad tears which could easily be extended by handling when wet must have their tears repaired before washing (Clapp, p. 61).

Wallpapers must be carefully and thoroughly supported, when being washed, on an open-meshed material which will not float and which is larger than the panel of wallpaper to facilitate lifting. The wallpaper may be immersed in a bath of water or wetted out with a gentle flow of water. Flowing water over the wallpaper while it is supported on a slant has the advantage of immediately removing the discoloured water which is produced. Slow and careful drying of the wallpaper following the washing is extremely important. Blotters are used to absorb the water and are changed as they become wet. The paper is weighted during drying to ensure that it will dry flat.

For more information and examples of the washing and drying processes, see: Clapp, pp. 61-65; Lee, Bachman and Fletcher, pp. 98-99; and Bosshard-Van der Bruggen, pp. 14-24.

5.0 DE-ACIDIFICATION

Treatments to remove acidity from paper are often called de-acidification treatments. They are carried out to prolong the life of the paper. A number of de-acidification treatments have been developed, but they are relatively new techniques and frequently have been changed and improved since the 1960s. No one type of treatment is universally applicable and all involve disadvantages and affect the paper in ways which are not yet fully understood or predictable. De-acidification should not, therefore, be undertaken without the recommendation and involvement of a professional conservator. For a fuller discussion of the problems and unresolved aspects of paper de-acidification, see Clapp, pp. 17-22.

Papers are usually de-acidified with mild alkalis which neutralize the acidity present in the paper and which, when exposed to the carbon dioxide of the air, change to nearly neutral carbonates. They remain in the fibres of the paper to act as a buffer, neutralizing further acidity which develops in the paper (Plenderleith and Werner, p. 56).

Non-aqueous methods of de-acidification have been developed for treatment of water-sensitive papers and those with

water-soluble paints and inks, but often these are not applicable to wallpapers because of the dangerous solvents and chemicals involved. One which is described by Plenderleith and Werner (pp. 57-58) uses a solution of magnesium methoxide in methanol (methyl alcohol), which, because of the toxicity of the methanol, should only be used in a protective environment such as a chamber with a fume hood. Even if protective clothing and a breathing apparatus are worn, methanol is inappropriate for in situ conservation in historic buildings, because it is highly flammable. The fire risk is unacceptable in buildings of historic interest, when alternative methods of de-acidification exist. This solution can be used to de-acidify wallpapers in conservation labs (Hamm and Hamm, p. 121).

Another more common de-acidification treatment is to spray or coat the wallpaper from the back with a solution or paste containing magnesium bicarbonate (produced by bubbling magnesium carbonate through carbon dioxide). At the Victoria and Albert Museum in London, a one percent solution of magnesium bicarbonate is usually used in the wallpaper adhesive. Three light coats of magnesium bicarbonate sprayed on the reverse side of the Van Rensselaer wallpaper in the Metropolitan Museum of Art increased the pH of the paper from 3.8 to 6.5 (Shelley, p. 133). Non-bath methods such as these do not give as good penetration or spread of the de-acidifying agent as immersion methods, but they are less dangerous to the wallpaper.

If a wallpaper can withstand aqueous techniques, a greater number of de-acidification treatments are possible. Washing wallpaper in a plain water bath helps to reduce acidity by washing away water-soluble acids. While this does not leave a buffering compound in the paper fibres to counteract future acidity, it may reduce the acidity to a level that is acceptable without further de-acidification treatment. If further treatment is required, the wallpaper may be immersed in a solution of magnesium bicarbonate in water or, as a two-step process, in a bath of lime water followed by a bath in a solution of calcium bicarbonate. Both of these aqueous methods do leave a precipitate in the paper fibres as a protective buffer (Plenderleith and Werner, pp. 56-57).

Preventive methods are the most important in dealing with acidity from external sources. Historic wallpapers must be hung on non-acidic lining papers or fabrics, and fragments mounted on acid-free mounting boards or non-acidic plastics. Pastes used in hanging them must be neutral or slightly alkaline (tested with indicator papers). Spaces in which historic wallpapers are hung or stored must be kept free of gaseous pollution and dust.

6.0 TEARS AND HOLES

Tears and holes sometimes can be left unrepaired if the wallpaper is to be relined with a lining paper which is similar in fibre and structure to the wallpaper itself. The lining paper can be dyed to tone with the colours of the wallpaper or inpainted to complete the pattern. In this way the appearance of the wallpaper is maintained without adding patches which may cause strains. Repairing tears and holes with small pieces of paper pasted into place has the disadvantage that the glued patches stretch less and may make the wallpaper difficult to reline. If there are many tears, however, it may be necessary to repair them before the wallpaper can safely be handled for other conservation treatments. The tears and holes constitute places of weakness which can easily be further torn and crumpled in handling.

Tears and holes are mended from the back of the paper, with paper similar to and thinner than that of the wallpaper. When machine-made paper is being repaired, the grain of the patch must be aligned with that of the paper (Plenderleith and Werner, p. 93). Handmade wallpaper is usually repaired with long-fibred, handmade Japanese paper, of a suitable thickness.

Small holes can be repaired by making a pulp of paper fibres with a small amount of paste. The hole is filled with this pulp and the paper is sandwiched between layers of blotting paper and weighted while drying. Techniques and suitable pastes for repairing tears are described in Clapp, pp. 67, 92-94; and Greenfield, pp. 12-27. For a description of mending a particular wallpaper, see Hamm and Hamm, pp. 119-21.

Tears and holes must not be repaired, even temporarily, with adhesive tapes. The tapes become hard and darkened with age, and the adhesive has a tendency to become absorbed into the paper, causing discolouration and brittleness. The adhesive of even the most longlasting tapes hardens and becomes difficult to remove. Adhesive tapes from earlier repairs to the wallpaper must be removed, carefully. The conservator may need to test the effects of various solvents on the sizing and colour of the wallpaper, before deciding which to use for removal of adhesive tape (Clapp, p. 55).

7.0 CREASES

Creases are removed by dampening (not wetting) the paper from the back to relax its shape and drying it flat under weights. For wallpapers printed in water-sensitive paints, or

paints which could easily be smudged or dislodged, only local treatment may be safe. These techniques are described in detail in Clapp, pp. 65-66. Attaching the relaxed wallpaper to a new, flat lining paper can also help to pull out creases.

Ironing can only be used locally for final drying of paper, and must be done without pressure. Ironing with pressure can flatten the paper too severely in the treated area only. Ironing also has the disadvantage of causing a difference in moisture content from the rest of the paper, which may result in temporary cockling (Clapp, p. 66).

8.0 PAINTS

For consolidation treatments for areas of flaking or brittle paints, see 3.2 above.

The group of paints containing green copper pigments, which not only fade but cause acidity, browning and brittleness in the adjacent paper, pose special conservation problems. Research is being conducted to find treatments which will thoroughly neutralize the copper green pigments. At present, however, treatment is limited to removal of the existing acidity in the green areas and replacement of lining papers (see Mairinger et al, pp. 180-85).

Preventive measures are an important part of the treatment of paint loss and fading. Control of heating, relative humidity and ventilation are essential in preventing paint loss through flaking, mould growths and insect attack. Control of light is required to slow down the rate of fading of pigments.

8.1 IN-PAINTING

Where the paint surface has already been lost, in-painting may be undertaken to restore the appearance of the wallpaper. In-painting is also used where pigments have faded or as over-painting where bad water stains cannot be removed from the wallpaper. It is a technique which must be applied skillfully however and to which careful consideration must be given before it is used on historically important wallpapers.

Since the wallpaper forms part of a decorative scheme which must meet the needs of the historic building as a whole, some amount of in-painting may be necessary. For historically-important wallpapers, the principles which have been developed for in-painting of wall mural painting should be followed. Techniques may be used, for instance, which suggest

the original form of the pattern and make it visually continuous without trying to replicate exactly the original work. For a careful consideration of these principles and their application, see Mora et al, pp. 301-15.

Materials for in-painting must be chosen carefully, so that the colours and gloss of paints will blend with the appearance of the wallpaper, both now and as they age. Distempers are no longer commercially available and preparing them from old recipes is generally expensive. Water colour paints are often used. As well, matte acrylic paints have been used to match original distemper paints.

The possibility of reversing the treatment at a later date is another important conservation requirement. The paints of in-painted areas will age differently than the older paints of the original wallpaper and the differences may become apparent quite quickly. For instance, the in-painting which was done in the 1930s on the Chinese wallpapers in the Saloon at the Royal Pavilion, Brighton, has already become discernible. While it is difficult to guarantee the later safe removal of in-painting, a paint which is believed to be removable should be chosen.

9.0 SURFACE COATINGS

Because they darken and become brittle with age and because they can damage the wallpaper beneath them, surface coatings (usually varnishes) may need to be removed.

Removal is carried out with solvents, that must be tested on small areas to determine which solvent will remove the surface coating satisfactorily. When solvents are to be used to remove varnish, they must also be tested carefully on the paper and the various paints of the wallpaper, as they may stain paper and stain or dissolve paints. The weakest possible solvent should be used. Removal is accomplished by carefully applying the solvent to the surface with repeated strokes of a soft brush or possibly by immersion in a bath of solvent. These are treatments which can easily harm the wallpaper and must be chosen and supervised by a professional conservator.

10.0 MOULDS

Active mould must be stopped immediately from spreading. This can sometimes be accomplished by carefully lowering the temperature and relative humidity. Increasing the tem-

perature to dry out walls quickly will encourage moulds to grow. Rapid drying with fans is not feasible either, as too-rapid drying at the surface of the wallpaper will cause loss of paint and other damage. Gradual drying by lowering the temperature and using dehumidifiers may be feasible, if the source of moisture can be eliminated. Wet wallpapers may need to be removed from walls for slow drying between layers of blotting paper or in conditions of controlled temperature and humidity. Or they may need to be refrigerated at about -20°C until conservation is possible (Clapp, p. 47).

Lowering the temperature and humidity stops active mould from growing, but does not kill it or eliminate the large number of spores which are present. Fumigation is often necessary to prevent continued outbreaks. Mould is first removed from the surface of the paper with tweezers or artists' brushes. The wallpaper is then fumigated, usually with thymol vapour in an air-tight cabinet. Wallpapers with oil paints or varnish coatings cannot be treated with thymol, since prolonged exposure to the vapour causes softening of these materials. They may instead be fumigated with ethylene oxide in a vacuum chamber. After fumigation, any remaining mould residues can be removed. Fumigation kills the existing mould growth and spores, preventing immediate re-contamination. Fumigation treatments do not, however, give lasting protection against future attack.

Eliminating the causes of dampness, improving ventilation and inspecting the wallpaper frequently for signs of mould growth are the most important steps to take in mould control.

11.0 INSECTS

If an insect infestation is discovered in a building, wallpaper must often be removed so that pastes, linings and structural wood can be treated. Many insecticides harm wallpaper which they contact. Solvent-based insecticides used on insect pests in wood will stain wallpaper, for example, and lindane can release free hypochlorous acid which will attack paper (Clapp, p. 41). If insects are present in the wallpaper itself, they can be killed by fumigating the wallpaper with ethylene oxide in a vacuum chamber (Clapp, p. 47).

As with moulds, the most important steps in avoiding insect damage are: prevention of damp, dark, poorly ventilated conditions; good housekeeping to ensure cleanliness; and periodic inspections for early detection.

12.0 BIBLIOGRAPHY

- Barrow, William.** 1963-74. *Permanence/Durability of the Book*. 7 Vols. The W.J. Barrow Research Laboratory, Richmond, VA.
- Bosshard-Van der Bruggen, Veronica.** 1975. *Report: On the Conservation of Wallpaper from Maison 40 in Quebec City*. Conservation Division, National Historic Parks and Sites, Ottawa.
- Clapp, Anne F.** 1978. *Curatorial Care of Works of Art on Paper*. 3rd revised ed. Intermuseum Conservation Association, Oberlin, OH.
- Fiedler, Andrea.** 1980. *Wall Decorations on Paper in Baroque Castles in Austria, Part II: Chinese Wallpapers and their Restoration*. Conservation within Historic Buildings. Vienna Congress. IIC, London, pp. 177-79.
- _____. 1974. *Rescuing Historic Wallpaper: Identification, Preservation, Restoration*. Technical Leaflet 76. American Association for State and Local History, Nashville.
- Frangiamore, Catherine Lynn.** 1977. *Wallpapers in Historic Preservation*. National Park Service. U.S. Department of the Interior, Washington, DC.
- Futernick, Robert.** 1981. "Conservation of Scenic Wallpapers: Sauvages de la Mer du Pacifique," *Journal of the American Institute for Conservation*, Vol. 20, No. 2 (Spring), pp. 139-46. Washington, DC.
- Greenfield, Jane.** 1981. *Paper Treatment*. Yale University Library, New Haven, CT.
- Hamburg, Doris A.** 1981. "The In Situ Conservation Treatment of a Nineteenth Century French Scenic Wallpaper," *Journal of the American Institute for Conservation*. Vol. 20, No. 2 (Spring), pp. 91-99. Washington, DC.
- Hamm, Patricia, and James Hamm.** 1981. "The Removal and Conservation Treatment of a Scenic Wallpaper, Paysage à Chasses, from the Martin Van Buren National Historic Site," *Journal of the American Institute for Conservation*. Vol. 20, No. 2 (Spring), pp. 116-25. Washington, DC.
- Jahoda, Karin, and Helga Rosenberger.** 1980. *Wall Decorations on Paper in Baroque Castles in Austria, Part I: The Chamber of Millions in the Palace of Schönbrunn*. Conservation within Historic Buildings. Vienna Congress. IIC, London, p. 176.
- Jennings, Arthur S.** 1903. *Wallpapers and Wallcoverings*. William T. Comstock, New York.
- Lee, Mary Wood, Konstanze Bachman and Shelley Fletcher.** 1978. *Sauvages de la Mer du Pacifique: Treatment of an Early 19th Century Wallpaper Depicting the Voyages and Death of Captain Cook*. In "Preprints of Papers Presented at the 5th Annual Meeting of the American Institute for Conservation of Historic and Artistic Works," Boston, MA, 30 May-2 June 1977." AIC Preprints, Washington, DC.
- Mairinger, Franz, et al.** 1980. *The Destruction of Paper by Green Copper Pigments*. Conservation Within Historic Buildings, Vienna Congress. IIC London, pp. 180-85.
- McClintock, Thomas K.** 1981. "The In Situ Treatment of the Wallpaper in the Study of the Longfellow National Historic Site," *Journal of the American Institute for Conservation*, Vol. 20, No. 2 (Spring), pp. 111-15.
- Mora, Paolo, Laura Mora and Paul Philippot.** 1984. *Conservation of Wall Paintings*. Butterworths, London.
- Phillips, Morgan.** 1980. "Adhesives for the Reattachment of Loose Plaster," *Bulletin of the Association for Preservation Technology*, Vol. 12, No. 2, pp. 37-63. Ottawa.
- _____. 1981. "Wallpaper on Walls: Problems of Climate and Substrate," *Journal of the American Institute for Conservation*, Vol. 20, No. 2 (Spring), pp. 83-90. Washington, DC.
- Plenderleith, H.J., and A.E.A. Werner.** 1971. *The Conservation of Antiquities and Works of Art*. 2nd ed. Oxford University Press, London.
- Richards, Nancy.** 1980. "Executed in Neatness of Pattern and Elegance of Colours: Reproduction Fabrics and Wallpapers," *Bulletin of the Association for Preservation Technology*, Vol. 12, No. 1, pp. 52-71. Ottawa.

Schulte, Elizabeth A. 1981. "Wallpaper Conservation at the Longfellow National Historic Site: Parlor and Dining Room," *Journal of the American Institute for Conservation*, Vol. 20, No. 2 (Spring), pp. 100-10. Washington, DC.

Shelley, Marjorie. 1981. "The Conservation of the Van Rensselaer Wallpaper," *Journal of the American Institute for Conservation*, Vol. 20, No. 2 (Spring), pp. 126-38. Washington, DC.

Smith, Richard D. 1975. "The De-acidification of Paper and Books," *American Libraries* (February), pp. 108-10.

Illustrations are the property of the Heritage Conservation Program, unless otherwise noted.

Canada

22709

